First Measurement of the Neutron Cross Section on Liquid Argon Between 100 and 800 MeV

Jorge Chaves
University of Pennsylvania
for the CAPTAIN collaboration

Neutrino Seminar
FNAL
05-09-19

CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos

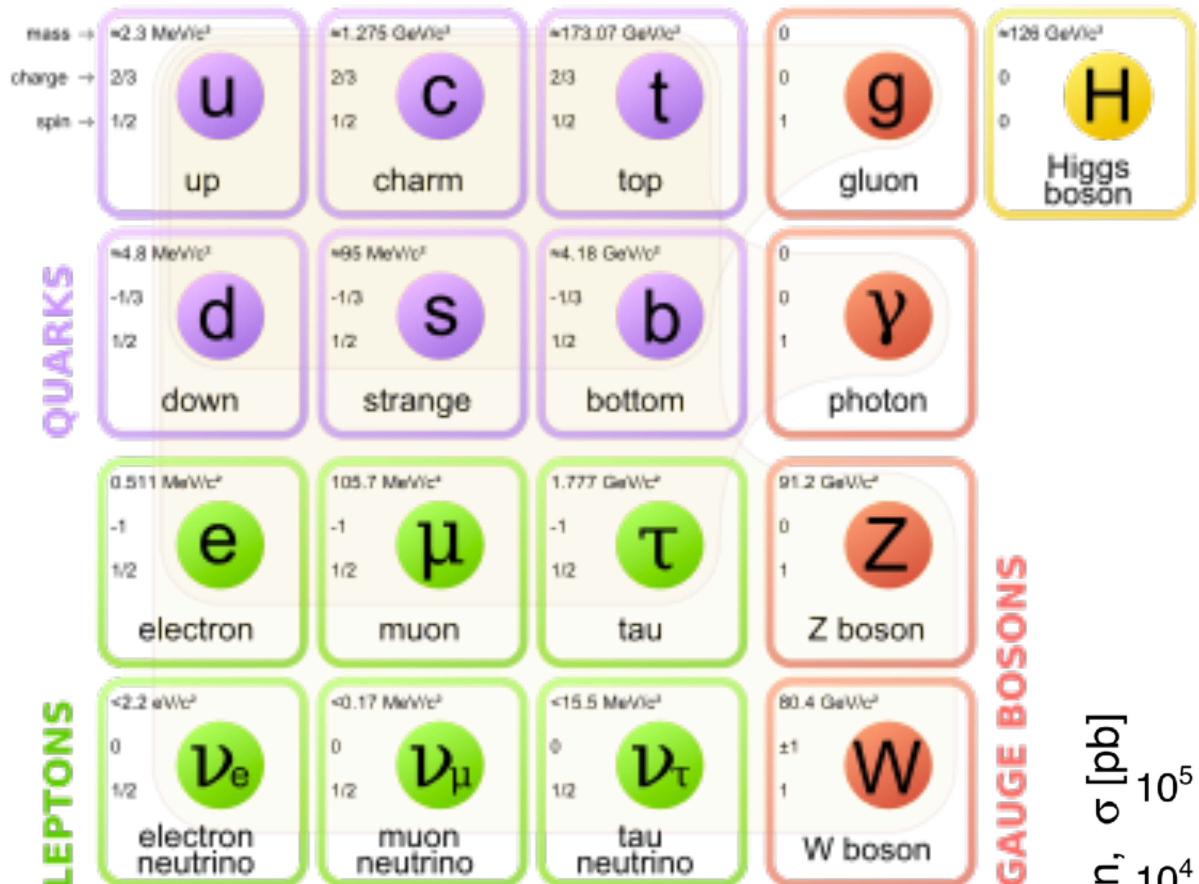
Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

Outline

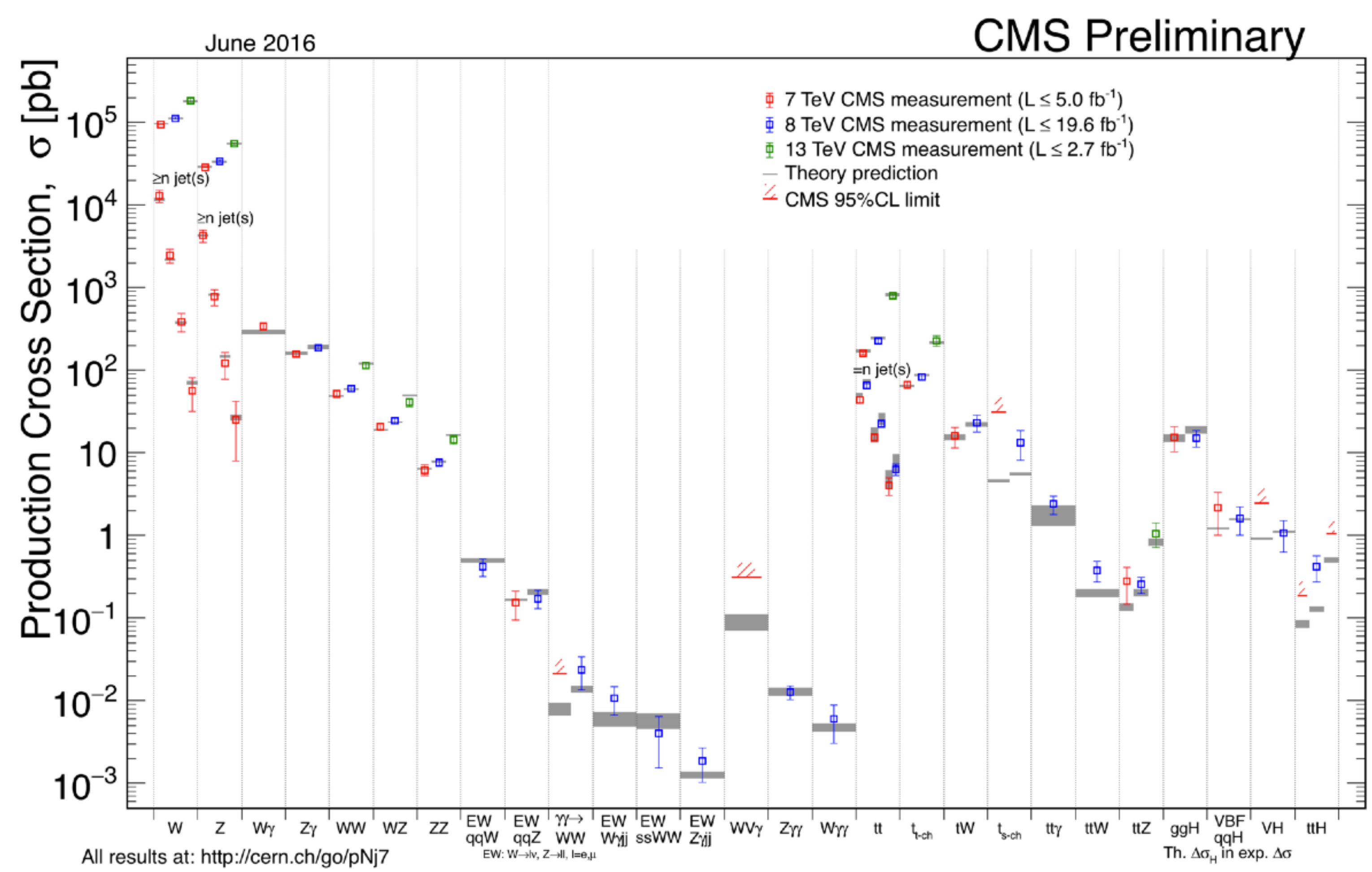
- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

Standard Model



$SU(3) \times SU(2)_L \times U(1)$

- Higgs boson discovery was a triumph of the SM
- Problems with SM:
  - Chiral structure of weak forces
  - Neutrino masses
  - Dark matter



Extremely successful!

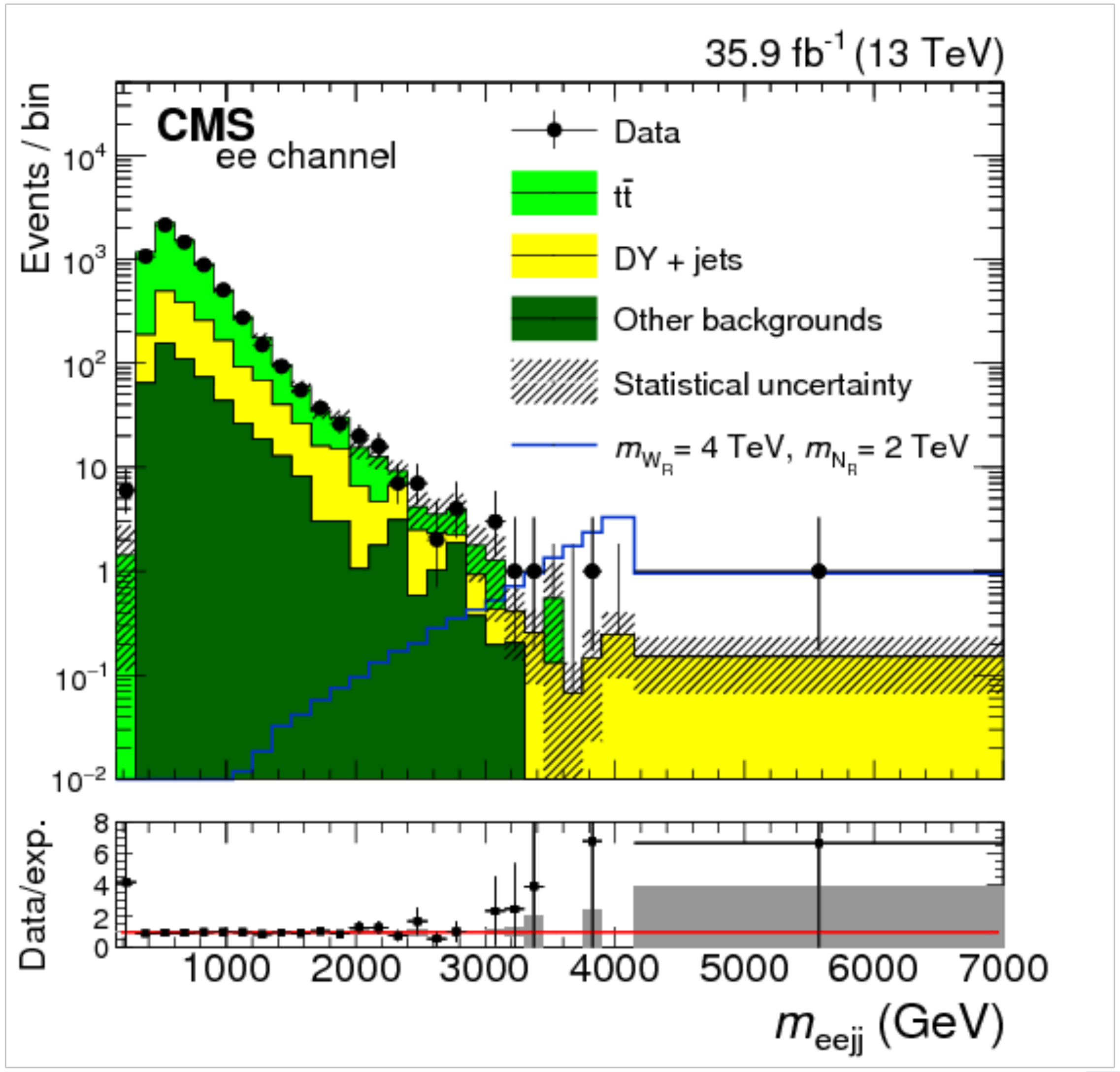
Jorge Chaves

Outstanding questions in the neutrino sector

- Neutrino mass (astronomical)
- Mass hierarchy (oscillation)
- Majorana vs. Dirac nature ($0\nu\beta\beta$)
- CP-violating phase (oscillation)
- Neutrino cosmology (joint efforts)

New physics in the neutrino sector

- Hints of new physics in experiments like LSND and MiniBooNE
  - Possibly sterile neutrinos
- See-saw heavy neutrinos
- Other BSM theories like chameleons, Mass Varying Neutrinos (MaVaNs)

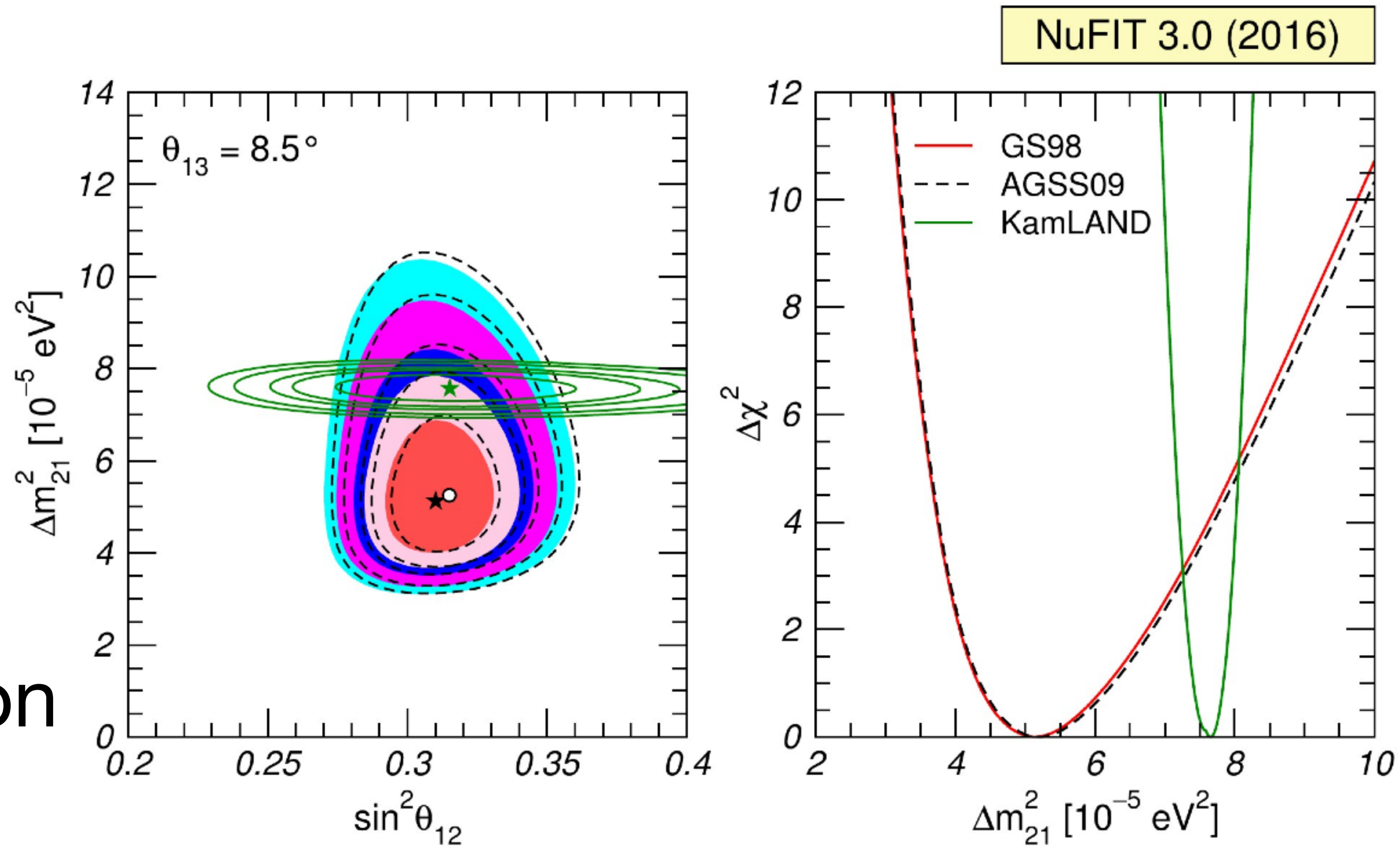


Neutrino oscillation parameters

$$\mathbf{U} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

atm **oscillation** **solar** **0νββ**

- 3 angles $(\theta_{12}, \theta_{13}, \theta_{23})$
- 1 Dirac phase δ
- 2 Majorana phases
- if δ≠0 implies CP-violation in the neutrino sector



Jorge Chaves

Neutrino oscillation probabilities

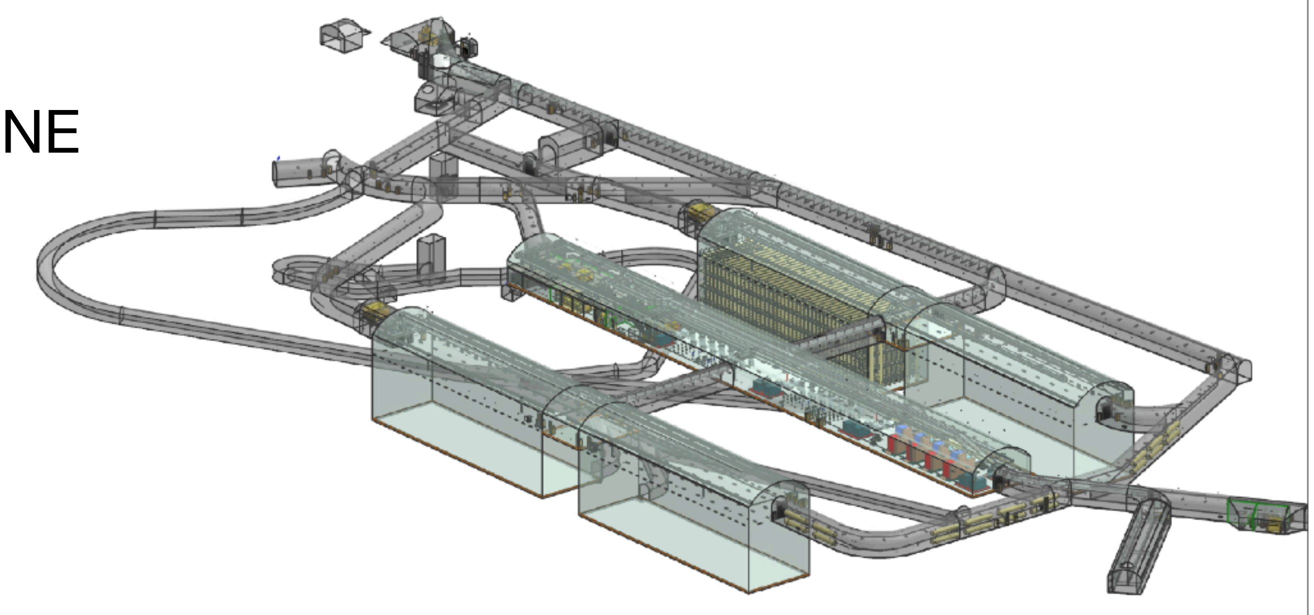
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+ 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

$$\frac{\Delta m^2\, c^3\, L}{4\hbar E} = \frac{\mathrm{GeV\,fm}}{4\hbar c} \times \frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E} \approx 1.27 \times \frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E},$$

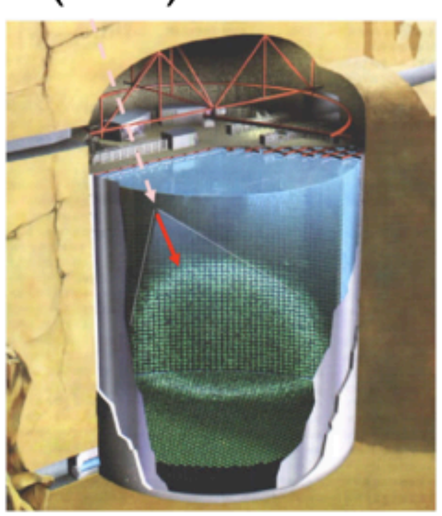
- Oscillation probability parametrized by two experimental parameters (L and E)
  - These are tuned when building experiment
- Measure the angles and mass difference parameter

Future neutrino experiments

- Next generation of experiments are preparing for the measurements
- Liquid argon time projection chamber: DUNE
- Water Cherenkov: Hyper-Kamiokande

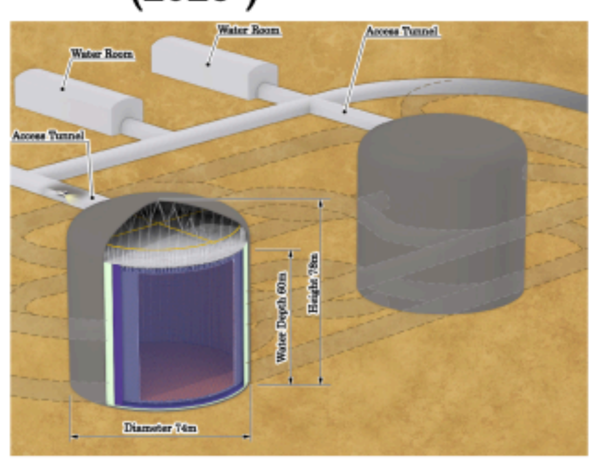


Super-Kamiokande
(1996-)



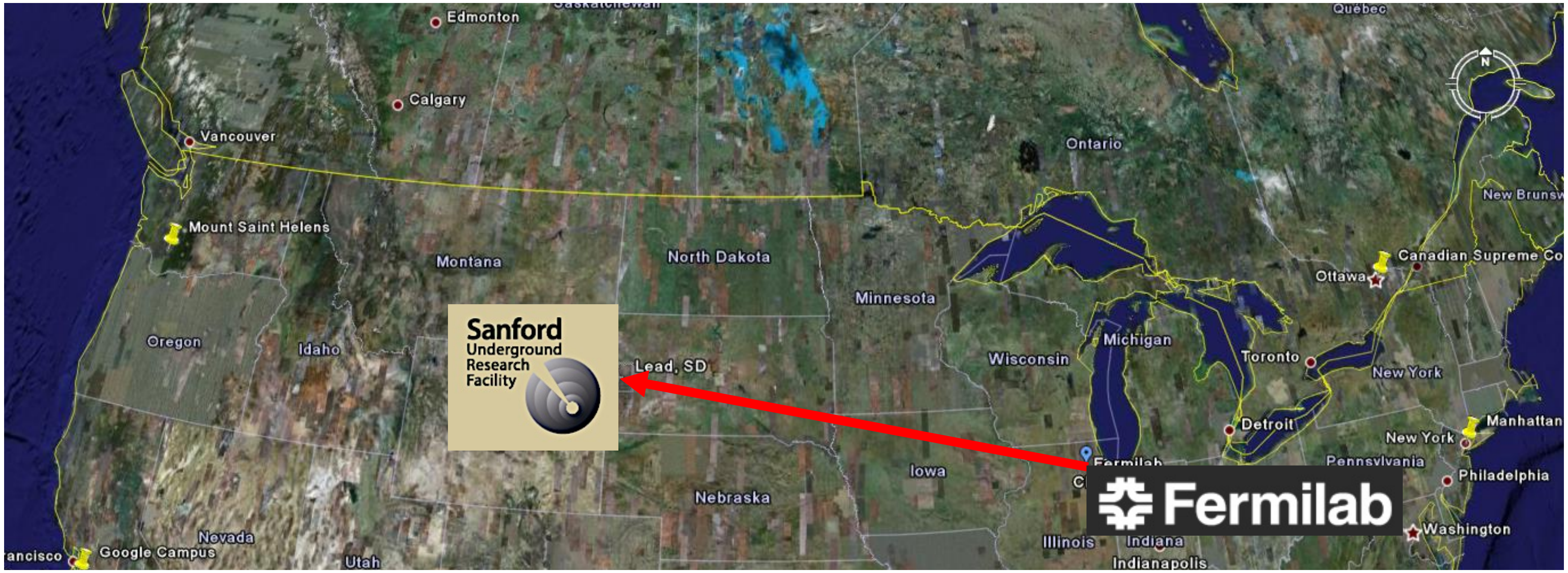
50 kton

Hyper-Kamiokande
(2026-)



520 kton

Future neutrino experiments - DUNE

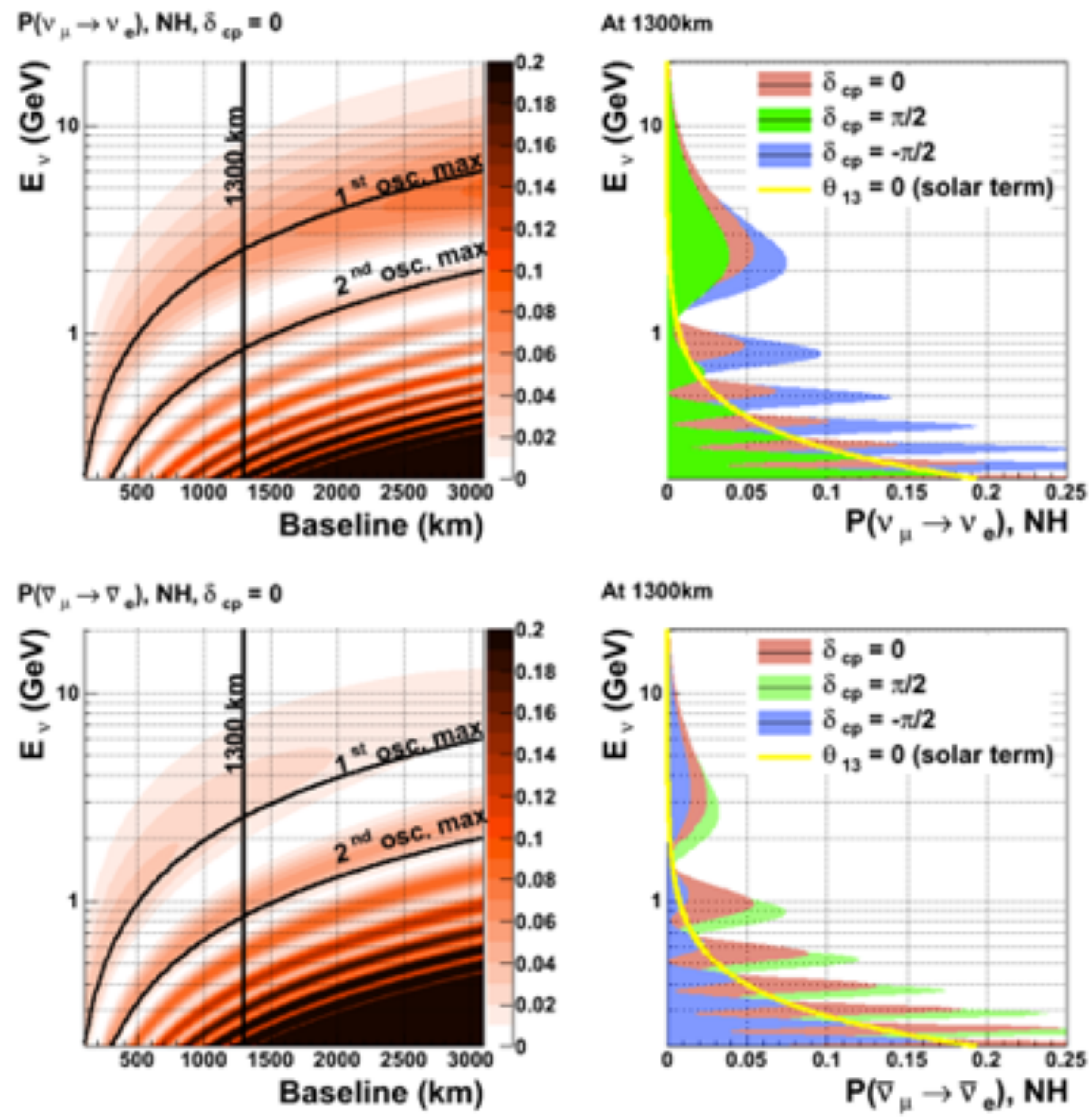


- DUNE = Deep Underground Neutrino Experiment
- Intense broad-band neutrino beam at Fermilab
- Near detector systems at Fermilab
- 40 kt liquid argon time-projection chamber (TPC) at Sanford Laboratory at 4850 foot depth – 1300 km from Fermilab
- Will have the longest manmade baseline of any neutrino experiment

Jorge Chaves

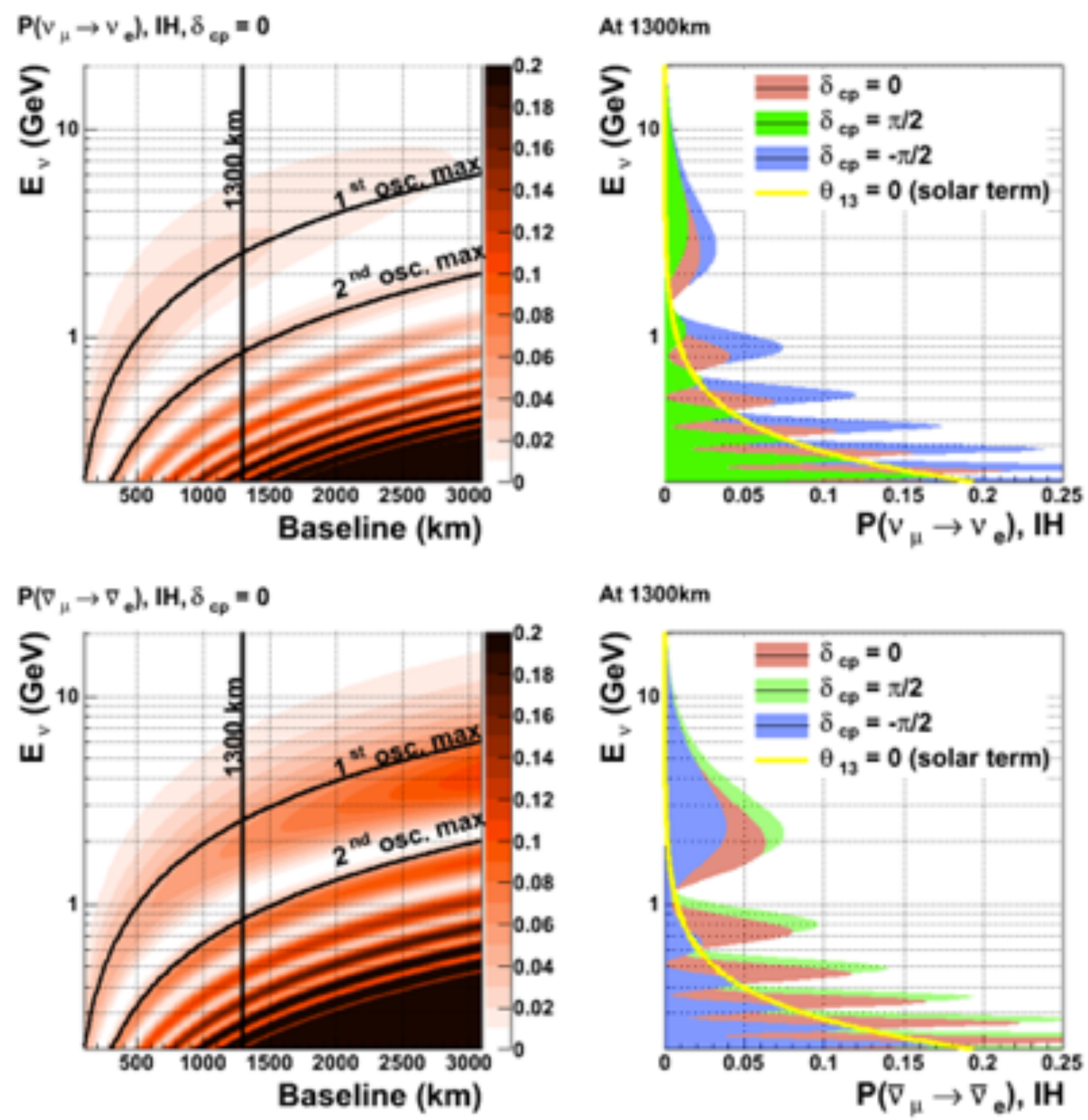
DUNE measurements

- Left plots: Neutrino oscillations vs energy and baseline for neutrinos (top) and antineutrinos (bottom) for $\delta_{CP} = 0$
- Right: Neutrino oscillations as a function of neutrino energy for different values of δ_{CP} for neutrinos (top) and antineutrinos (bottom) – solar term shown in yellow
- All plots assume Normal Mass Ordering

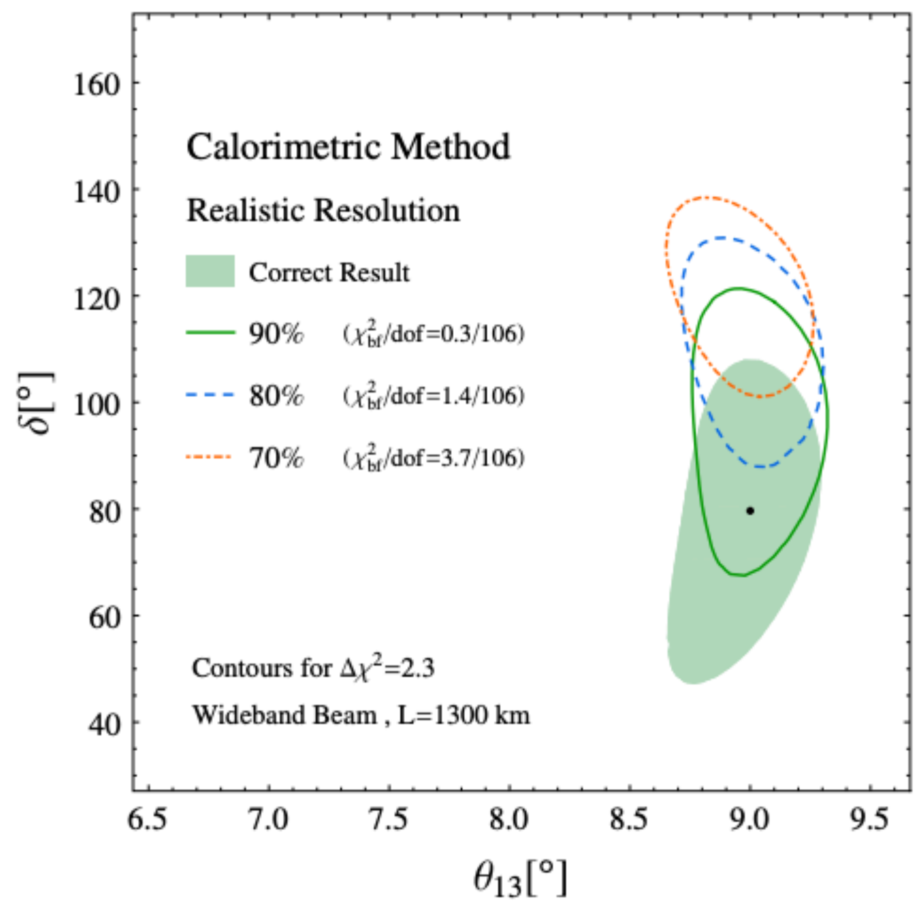


DUNE measurements

- Left plots: Neutrino oscillations vs energy and baseline for neutrinos (top) and antineutrinos (bottom) for $\delta_{CP} = 0$
- Right: Neutrino oscillations as a function of neutrino energy for different values of δ_{CP} for neutrinos (top) and antineutrinos (bottom) – solar term shown in yellow
- All plots assume Inverted Mass Ordering

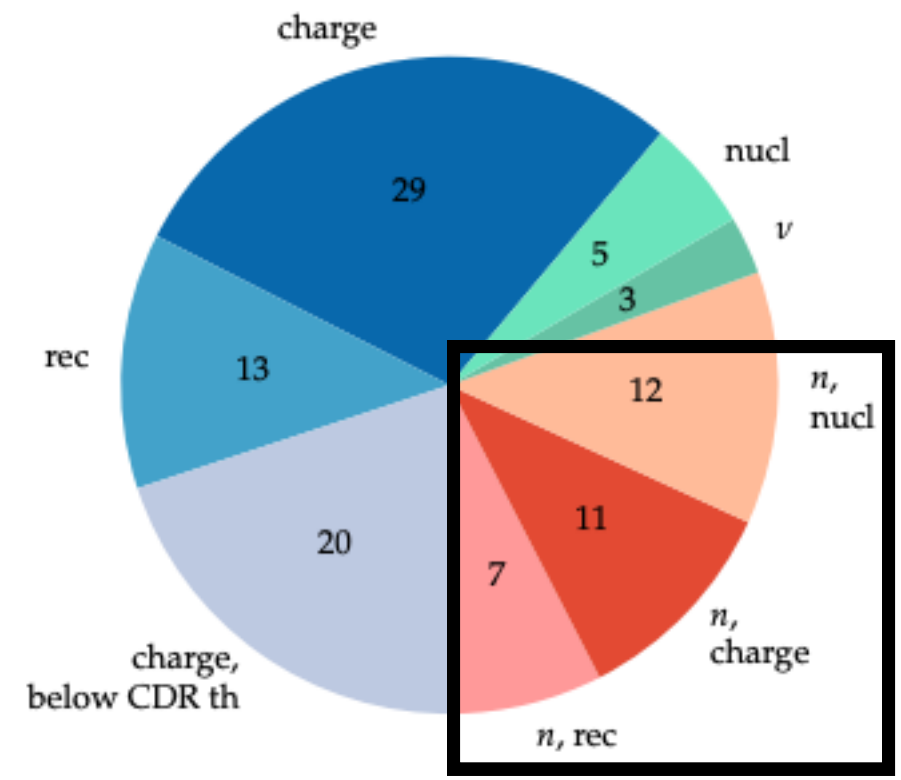


Missing energy from neutrons in DUNE



Phys. Rev. D 92, 091301 (2015)

Hadronic energy budget



30% to neutrons

arXiv:1811.06159

- Authors simulated neutrino events with neutrons in them
- Left: Measured parameters are shifted from true value due to missing energy
- Right: The energy budget of hadrons in neutrino interactions with a large fraction going to neutrons

CAPTAIN collaboration

- University of Alabama: Ion Stancu
- LBL: Craig Tull
- BNL: Hucheng Chen, Veljko Radeka, Craig Thorn
- UC Davis: Daine Danielson, Steven Gardiner, Emilja Pantic, Robert Svoboda
- UC Irvine: Jianming Bian, Scott Locke, Michael Smy
- UC Los Angeles: David Cline, Hanguo Wang
- UC San Diego: George Fuller
- University of Hawaii: Jelena Maricic, Marc Rosen, Yujing Sun
- University of Houston: Lisa Whitehead Koerner
- LANL: Elena Guardincerri, Nicolas Kamp, David Lee, William Louis, Geoff Mills, Jacqueline Mirabal-Martinez, Jason Medina, John Ramsey, Keith Rielage, Constantine Sinnis, Walter Sondheim, Charles Taylor, Richard Van de Water, Peter Madigan, Qiuguang Liu
- University of New Mexico: Michael Gold, Alexandre Mills, Brad Philipbar
- New Mexico State: Robert Cooper
- University of Pennsylvania: Connor Callahan, Jorge Chaves, Shannon Glavin, Avery Karlin, Christopher Mauger
- SUNY Stony Brook: Neha Dokania, Clark McGrew, Sergey Martynenko, Chiaki Yanagisawa

CAPTAIN Physics Program

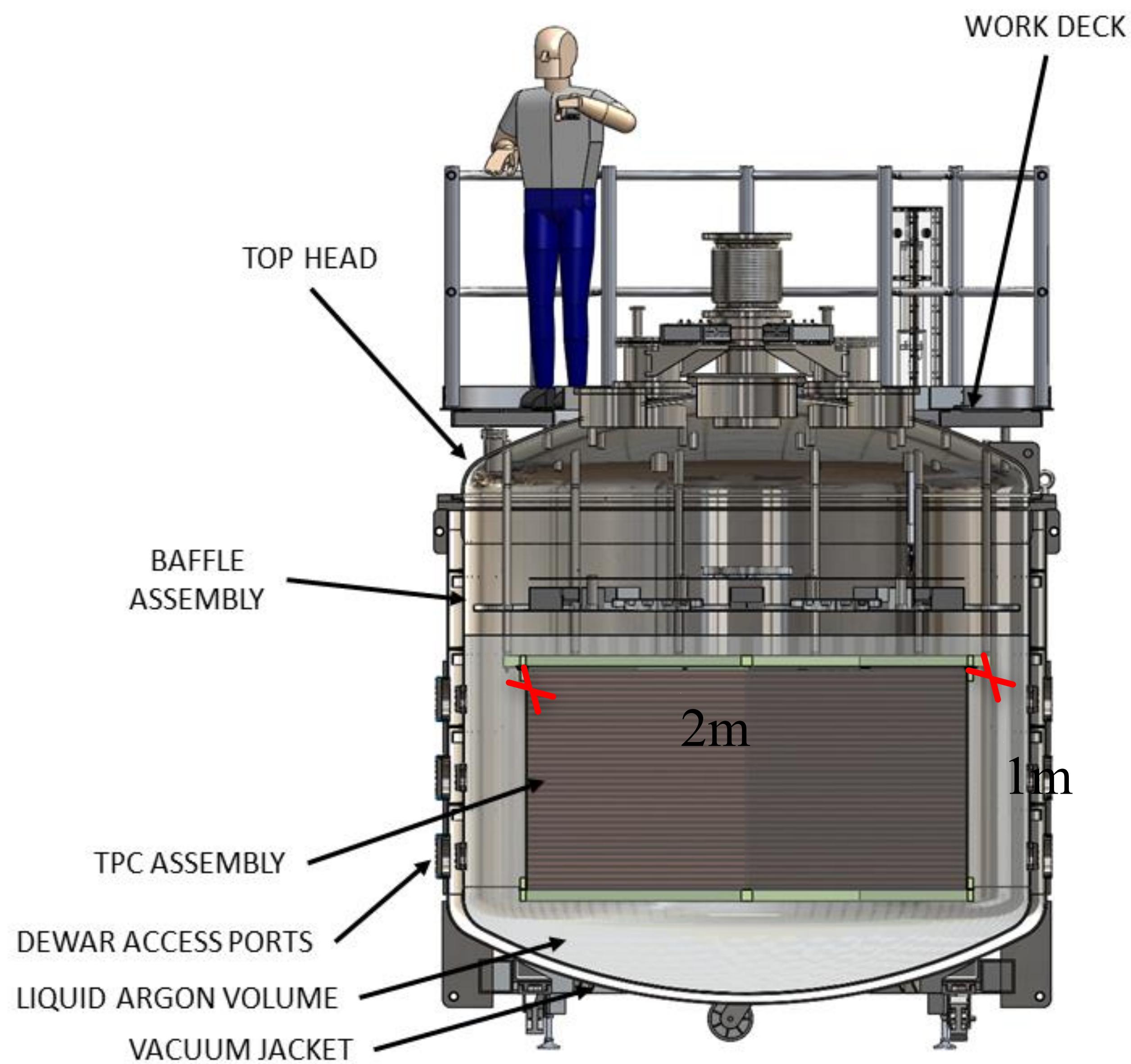
- CAPTAIN is a 1m-long drift liquid Argon TPC (LArTPC) designed to make measurements relevant for the DUNE experiment
- Medium-energy neutrino physics ~100 MeV to 5 GeV~ (Neutron Beam):
  - Measure neutron interactions and event signatures (e.g. pion production) to allow us to constrain number and energy of emitted neutrons in neutrino interactions (at DUNE, mean neutron K.E. from the LBNF beam ~ 400 MeV)
  - Measure higher-energy neutron-induced processes that could be backgrounds to ν_e appearance e.g. $^{40}Ar(n,\pi_0)^{40}Ar(*)$
- Low-energy neutrino physics ~below 100 MeV~ (Neutrino Beam):
  - Measure the neutrino CC and NC cross-sections on Argon in the same energy regime as supernova neutrinos
  - Measure the correlation between true neutrino energy and visible energy for events of supernova-neutrino energies

Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

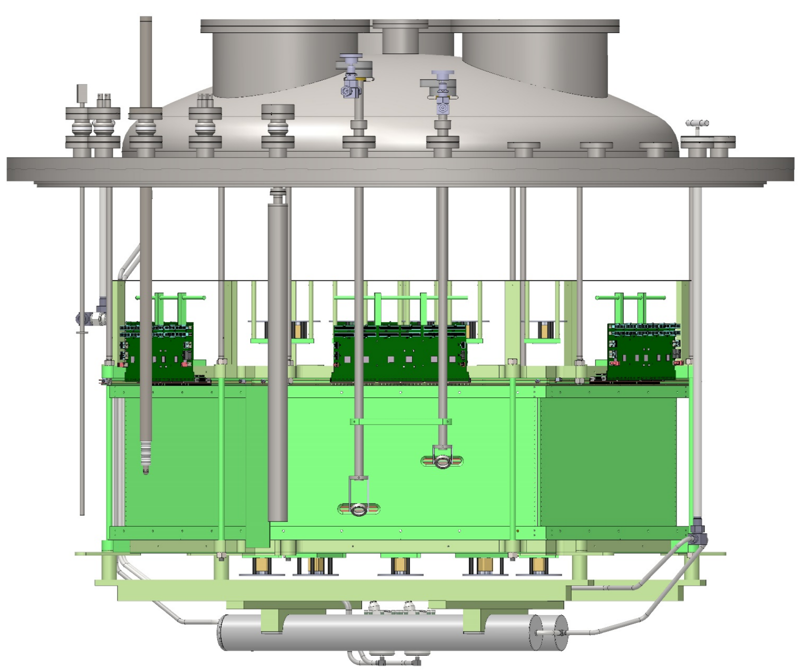
CAPTAIN detector

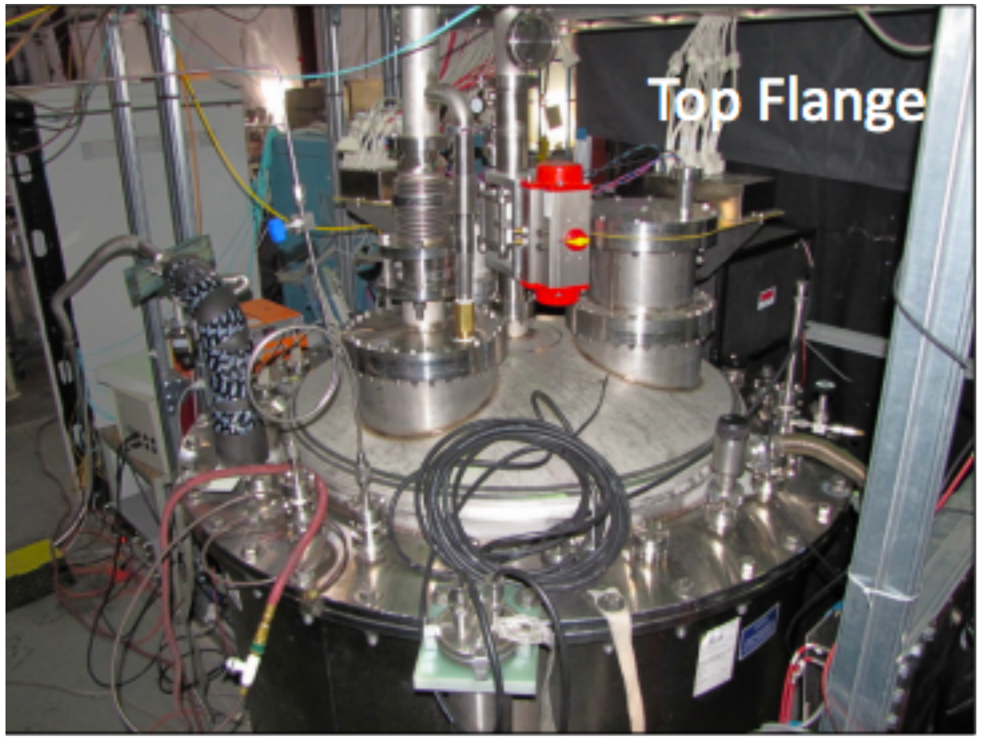
- Cryostat
  - Capacity: 10 tons
- TPC
  - Hexagonal prism with 1m vertical drift, 1m apothem, 2000 channels, 3mm pitch, 5 instrumented tons
- Photon detection system
- Laser calibration system
- Same cold electronics and electronics chain as MicroBooNE



CAPTAIN prototype (Mini-CAPTAIN)

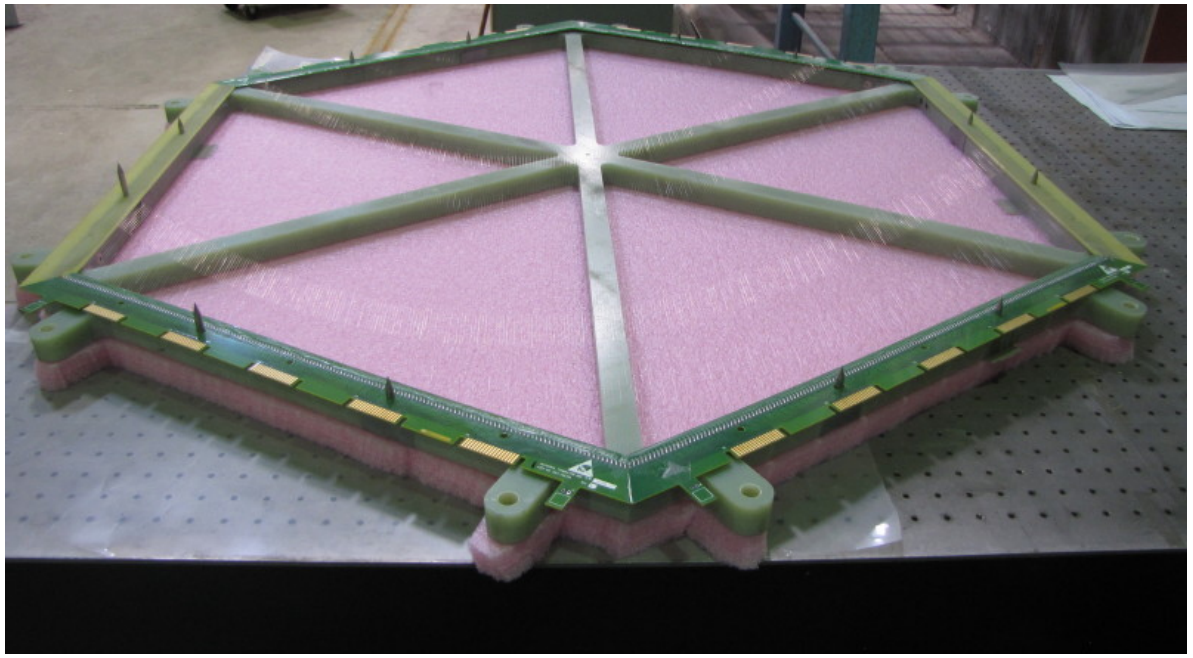
- 400 kg instrumented hexagonal TPC with 32 cm drift, 50 cm apothem
- ~1000 channels, 3 mm wire pitch
- 24 x 6 cm^2 PMT light detection system
    - 21 in actual operation
- Same cold electronics and electronics chain as MicroBooNE

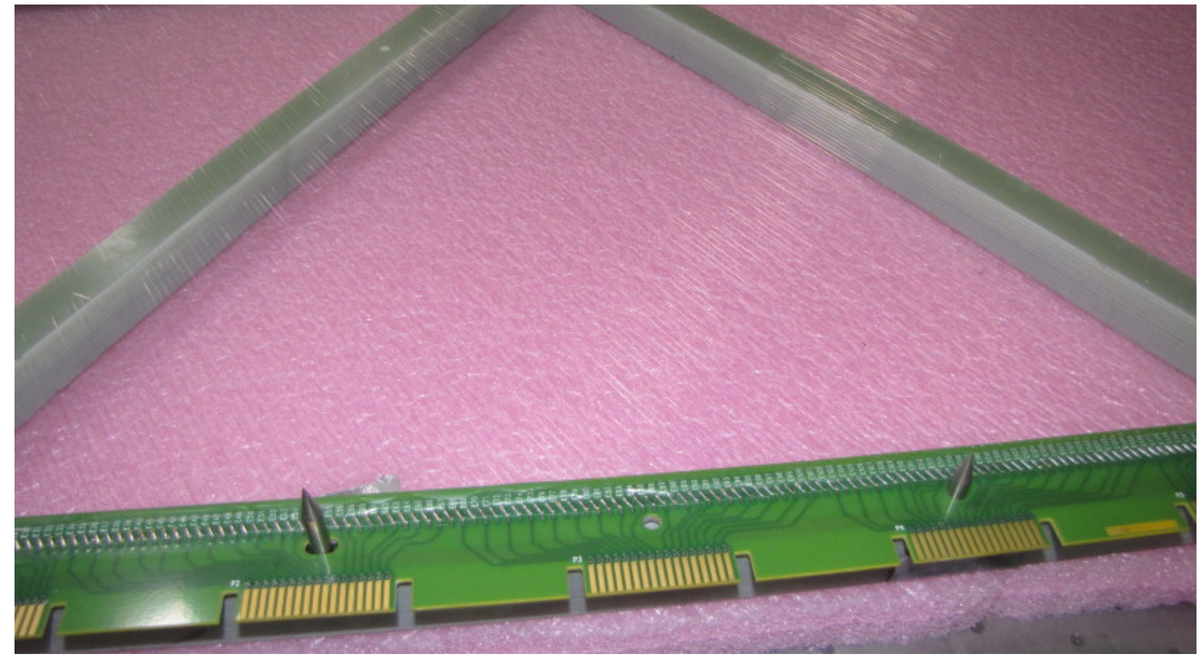


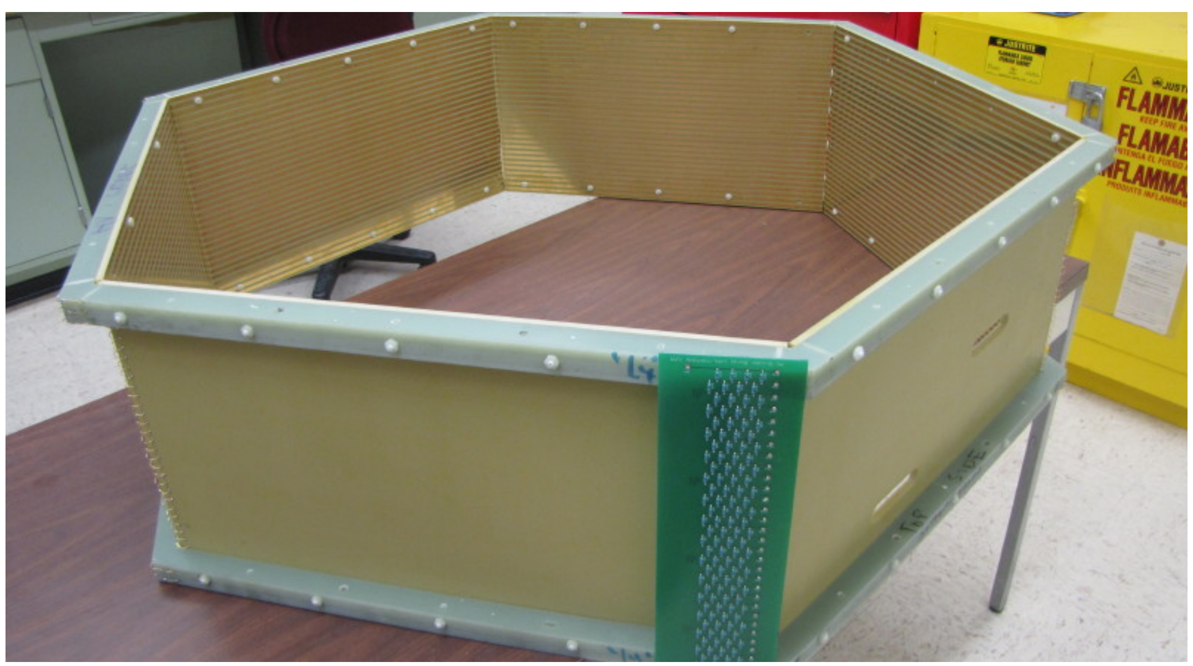


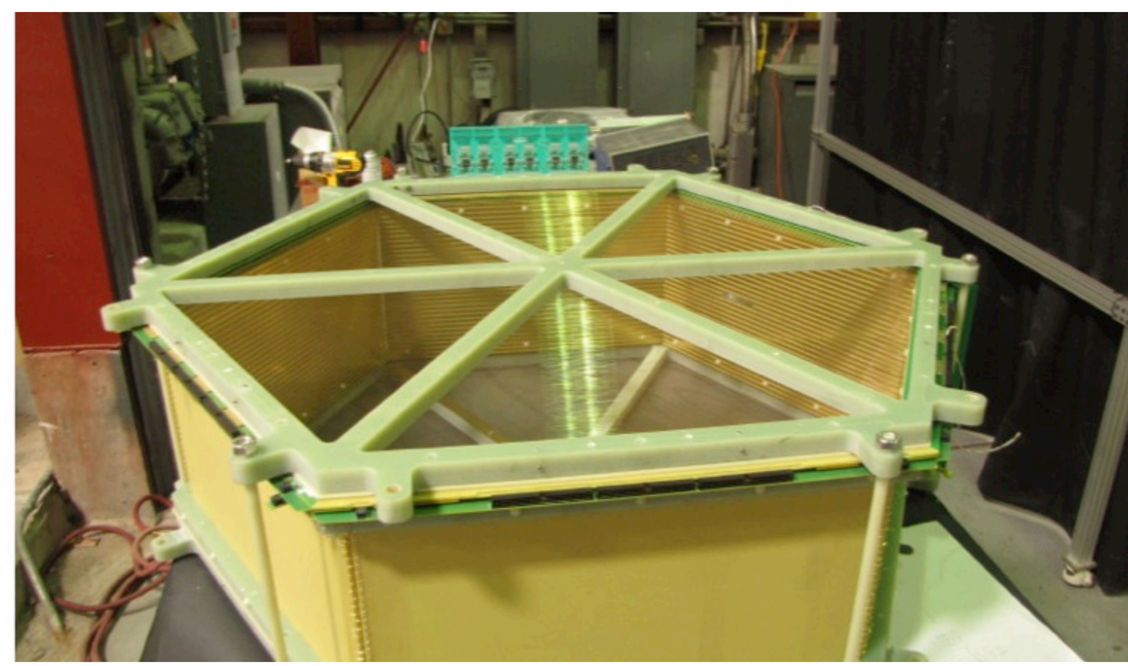
Jorge Chaves

MiniCAPTAIN assembly

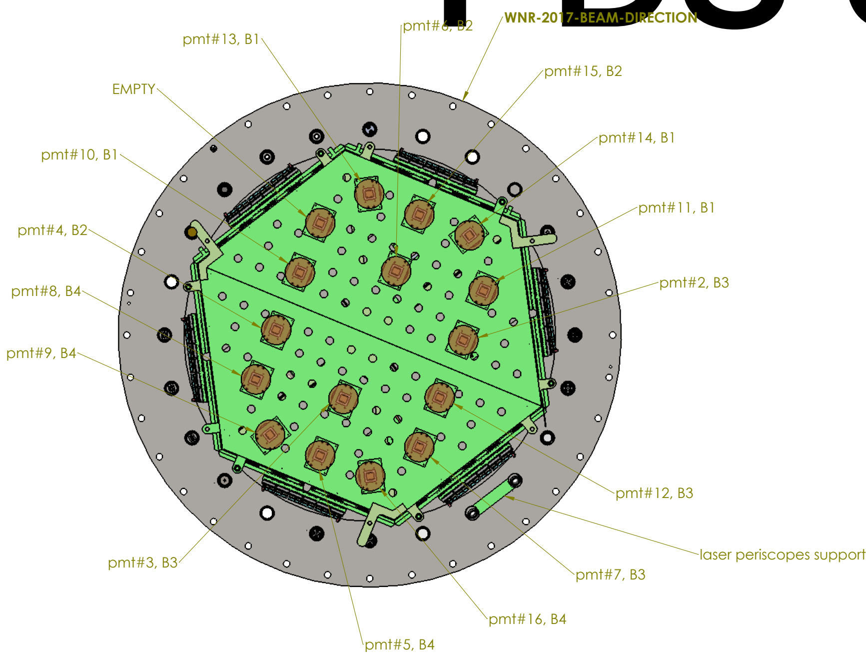


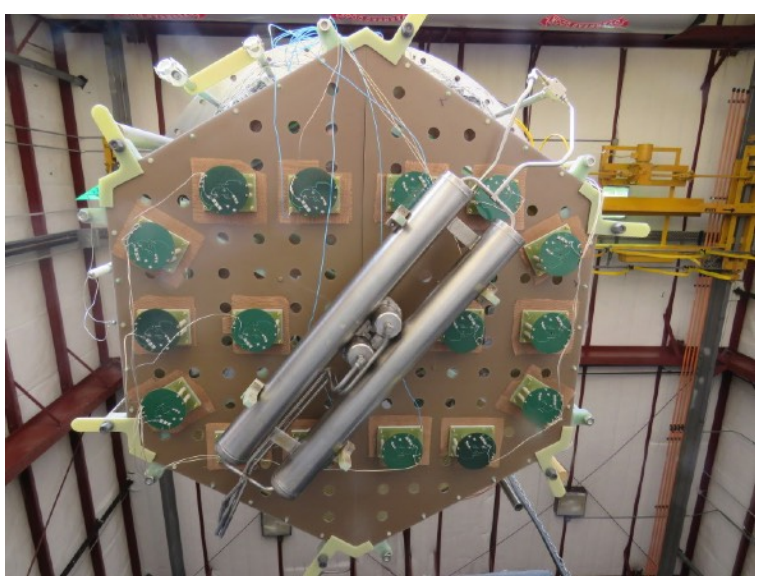




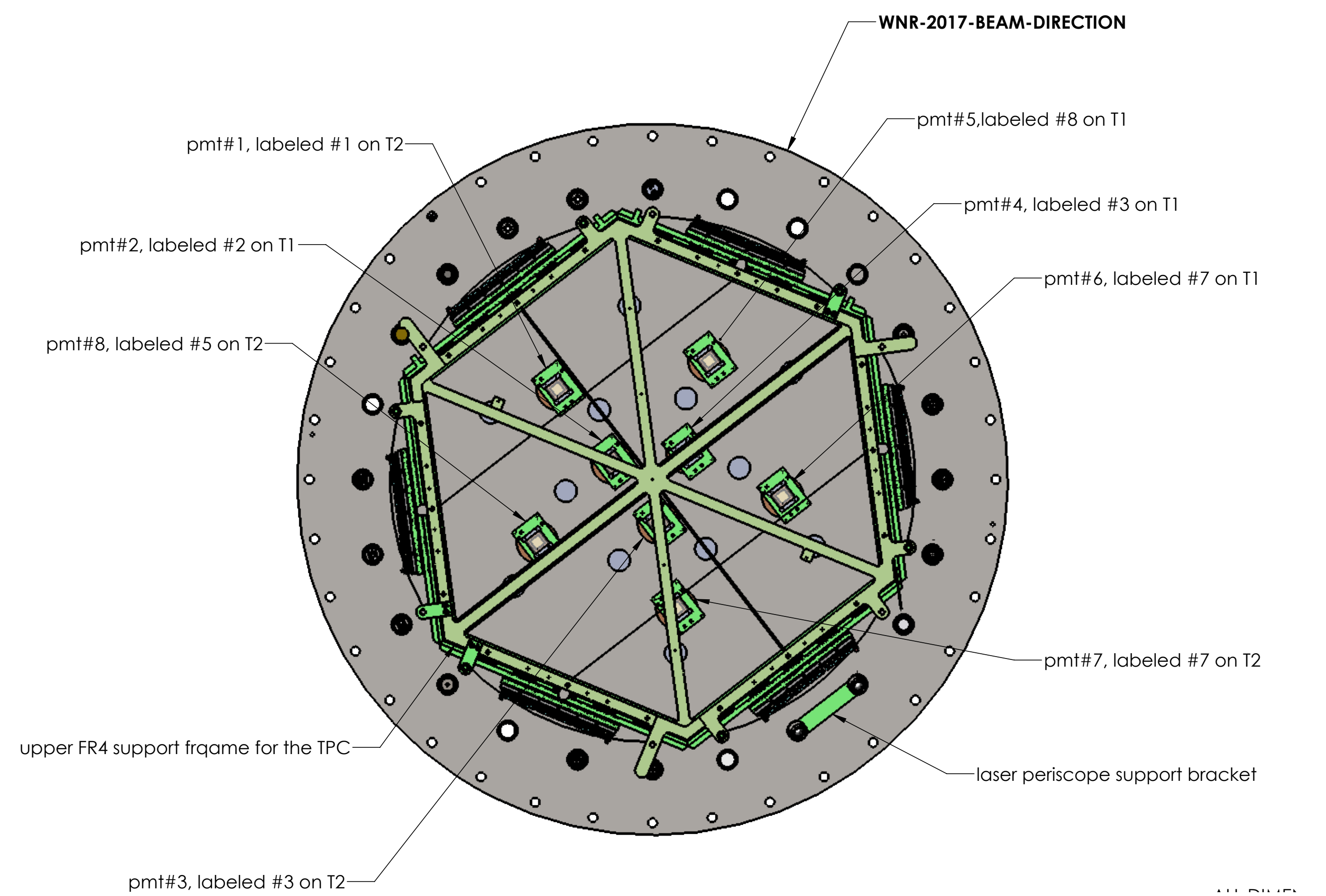


Mini-CAPTAIN PDS diagrams





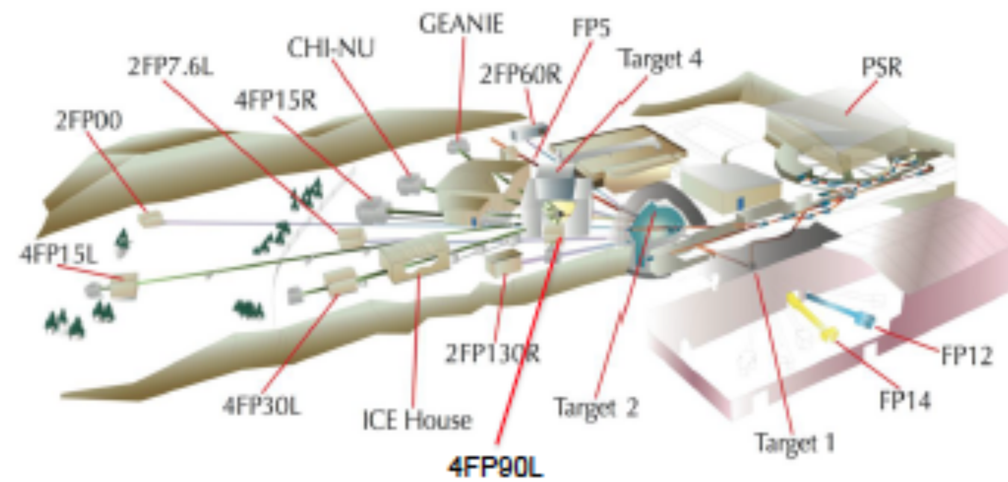
Bottom view of the PDS

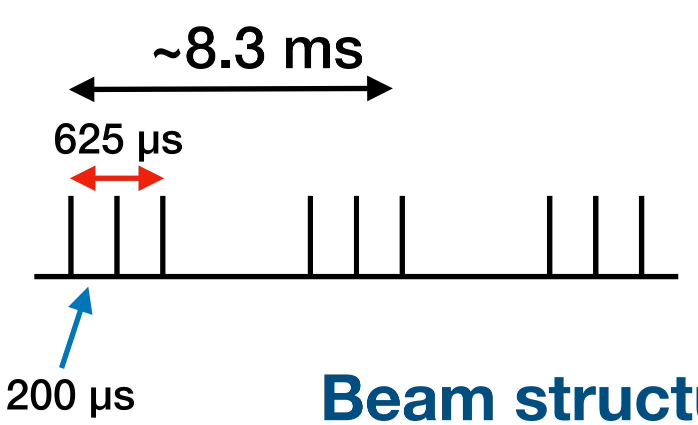


Top view of the PDS

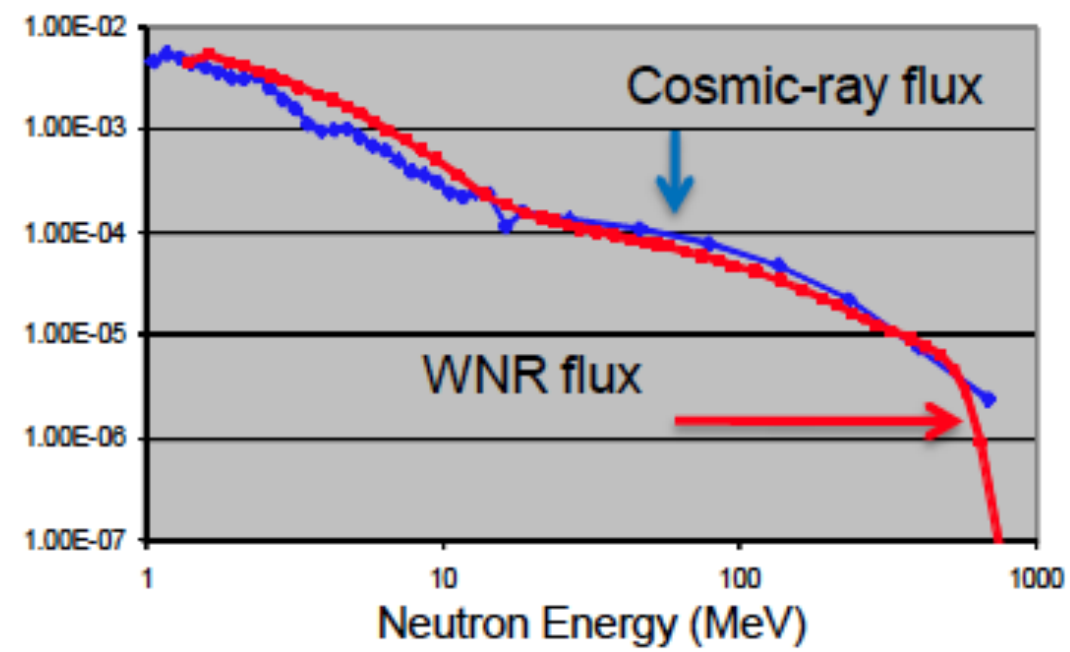
Neutron beam at LANSCE

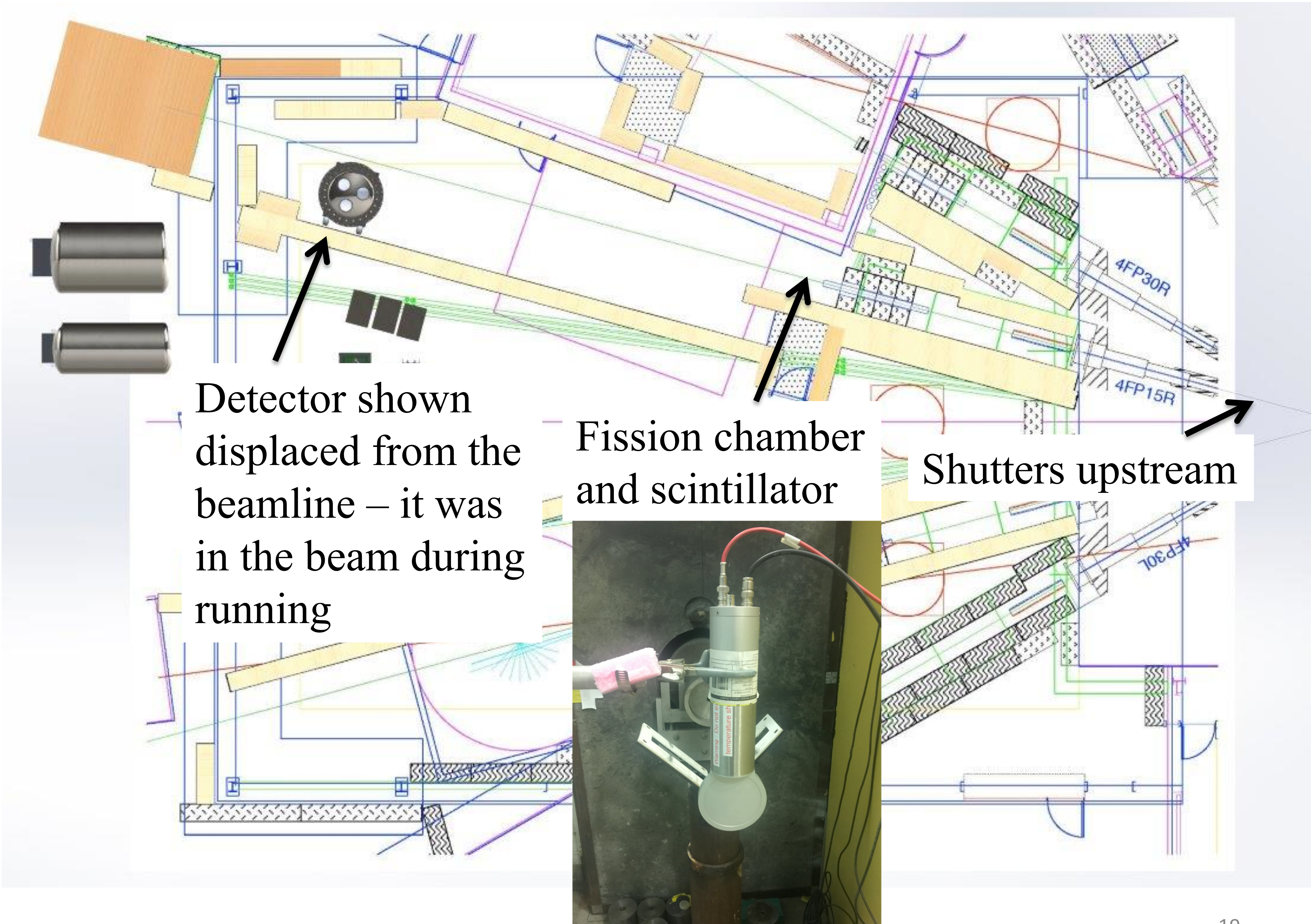
- Los Alamos Neutron Science Center WNR facility provides a high flux neutron beam with a broad energy spectrum similar to the cosmic-ray spectrum at high altitude.
- Nominal time structure of the beam: micro pulses 1.8 μs apart within a 625 μs long macro pulse.
- Most users of these facilities want more neutrons, but we wanted fewer.
- CAPTAIN special run of 3 micro pulses 200 μs apart per macro pulse.
- Shutter to control flux to detector allowed us to further control intensity.





Beam structure

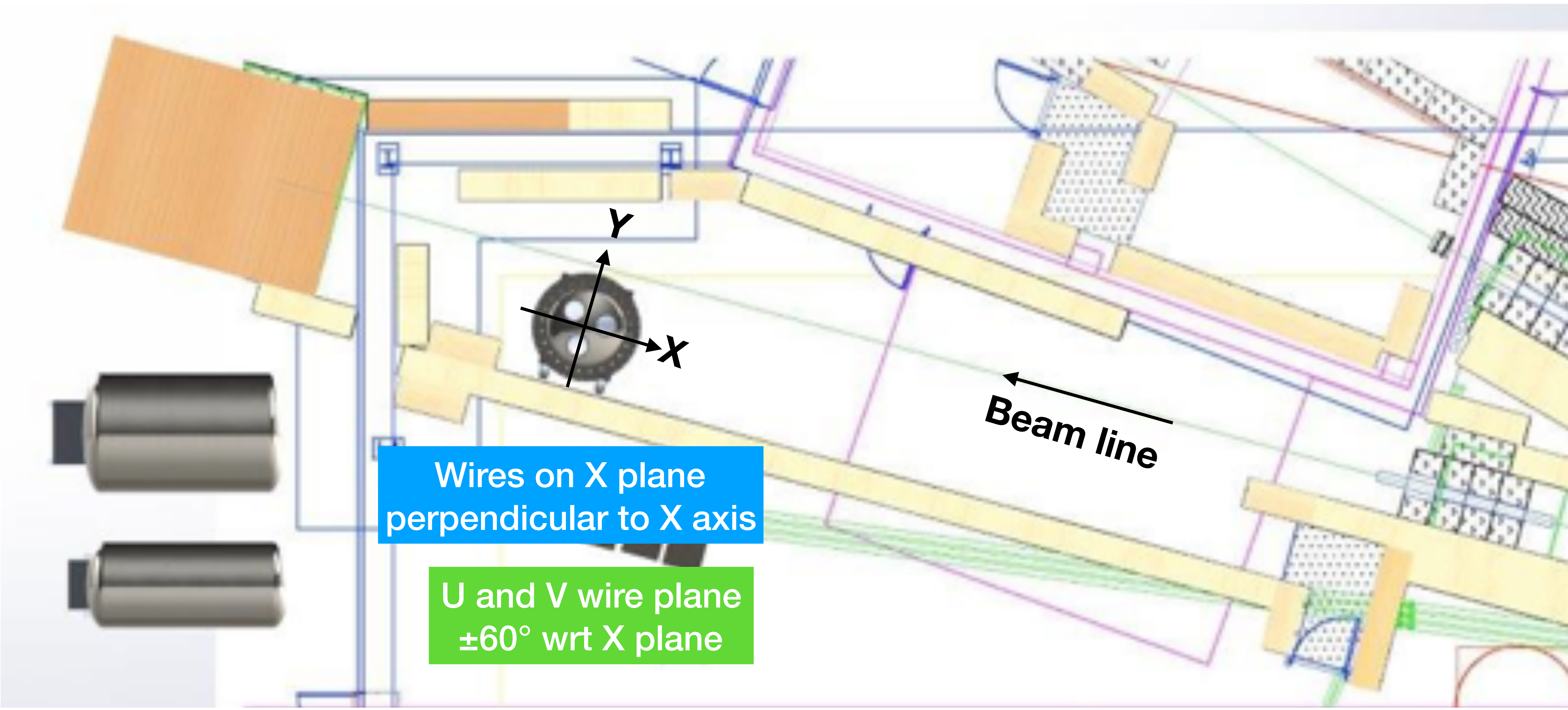




19

Jorge Chaves

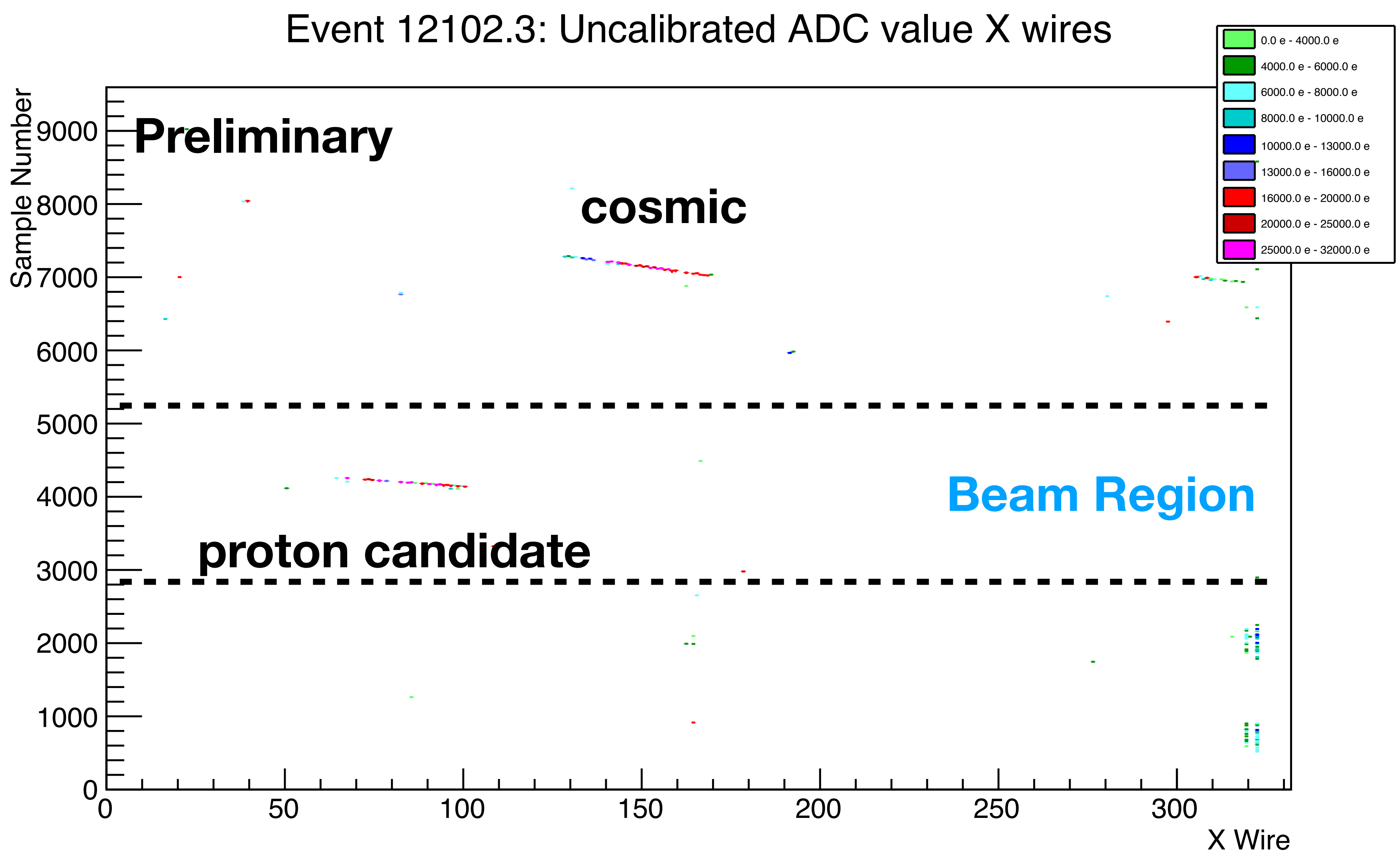
Detector coordinates



Triggering Mini-CAPTAIN

- Beam facility provides an RF signal for every micro pulse that is then distributed to TPC and PDS.
- TPC takes data for 5 ms when the first RF from a macro pulse is received.
    - 1 ms of buffered pretrigger data.
    - ~3.5 ms of no-beam data. Cosmics collected during this time.
- All 3 micro pulses of a macro pulse fall within the same TPC acquisition window.
- PDS receives the RF signal independently and needs to be synced with TPC.

Tracks from 2017 run



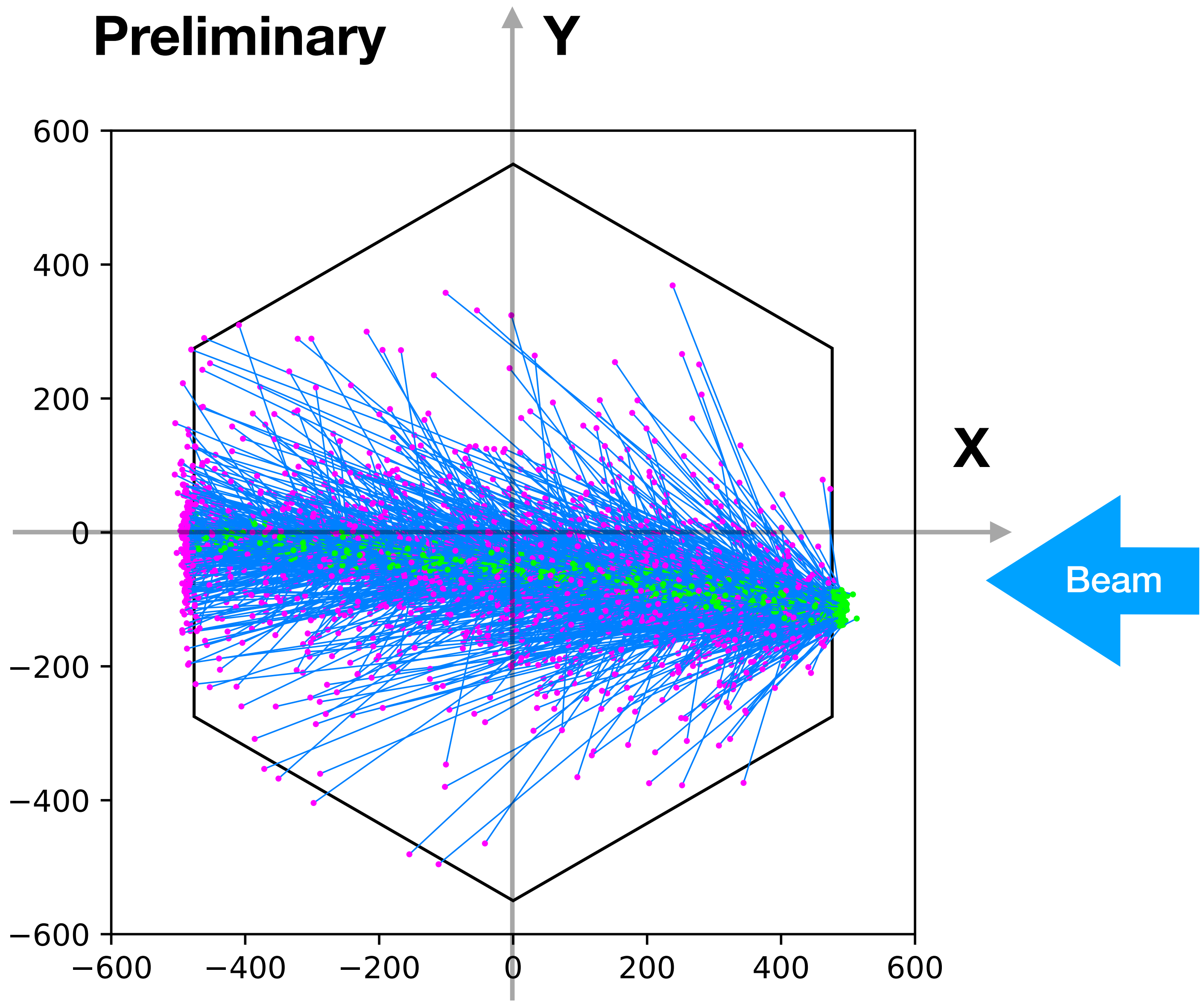
Neutron event from low intensity run

- Full TPC and PDS used in the 2017 Physics Run : July 23 – Aug 05
- Special low intensity run taken on July 31st.

Jorge Chaves

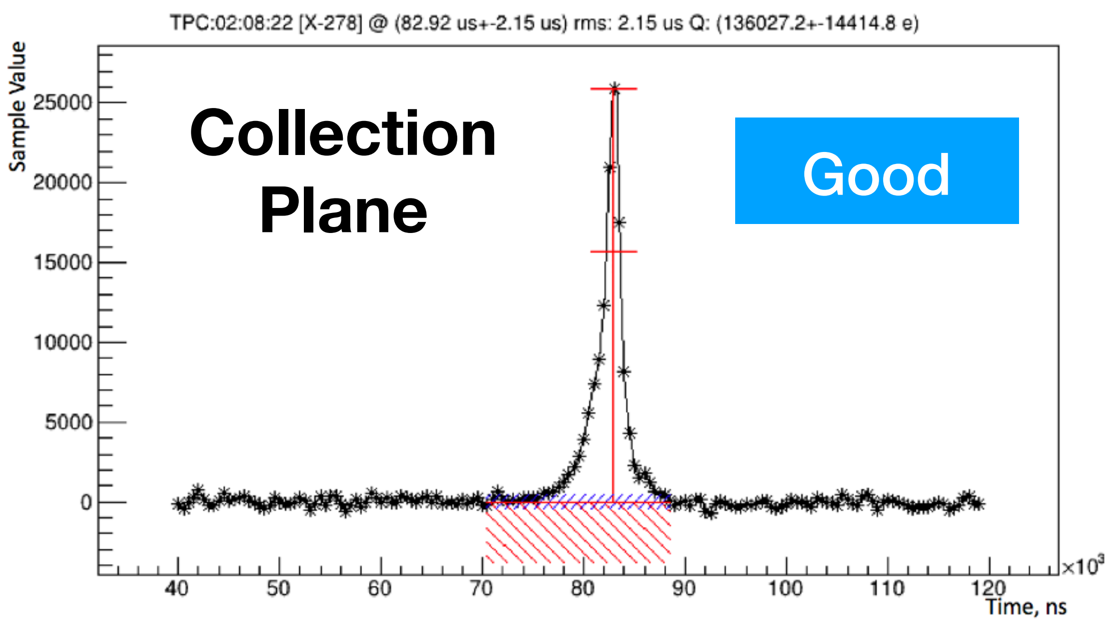
Tracks in Mini-CAPTAIN

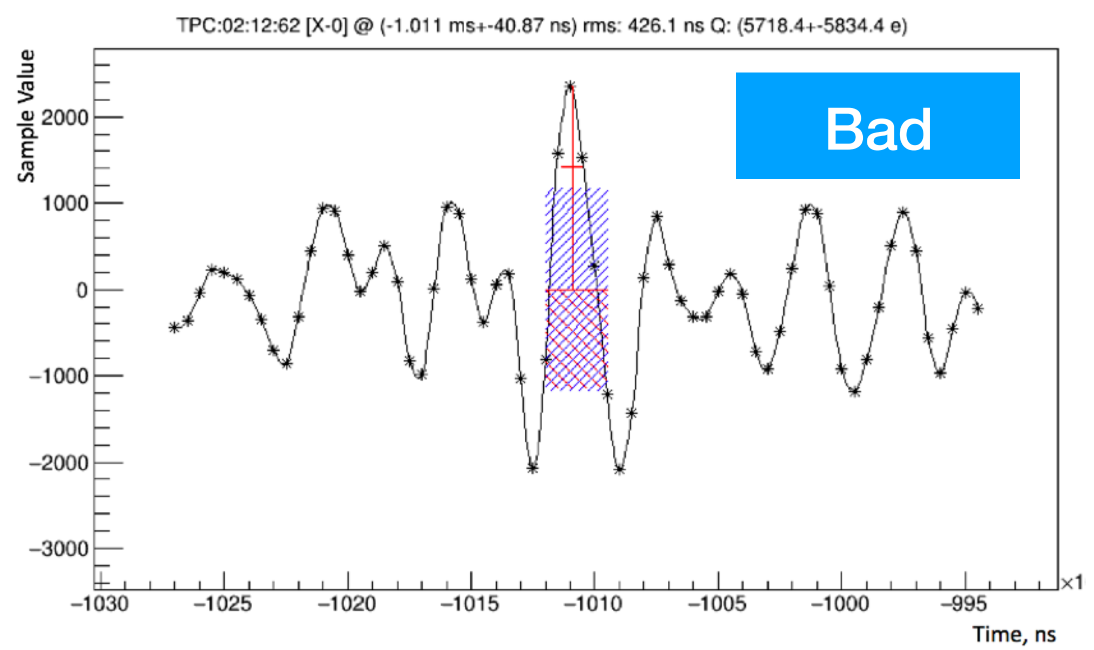
- Two-dimensional projection of the detector.
- Low intensity beam with ~1 neutron every 6 micro pulses.
- Detector is slightly rotated with respect to beam line.
- Plenty of cosmics and perhaps secondary interactions.



Jorge Chaves

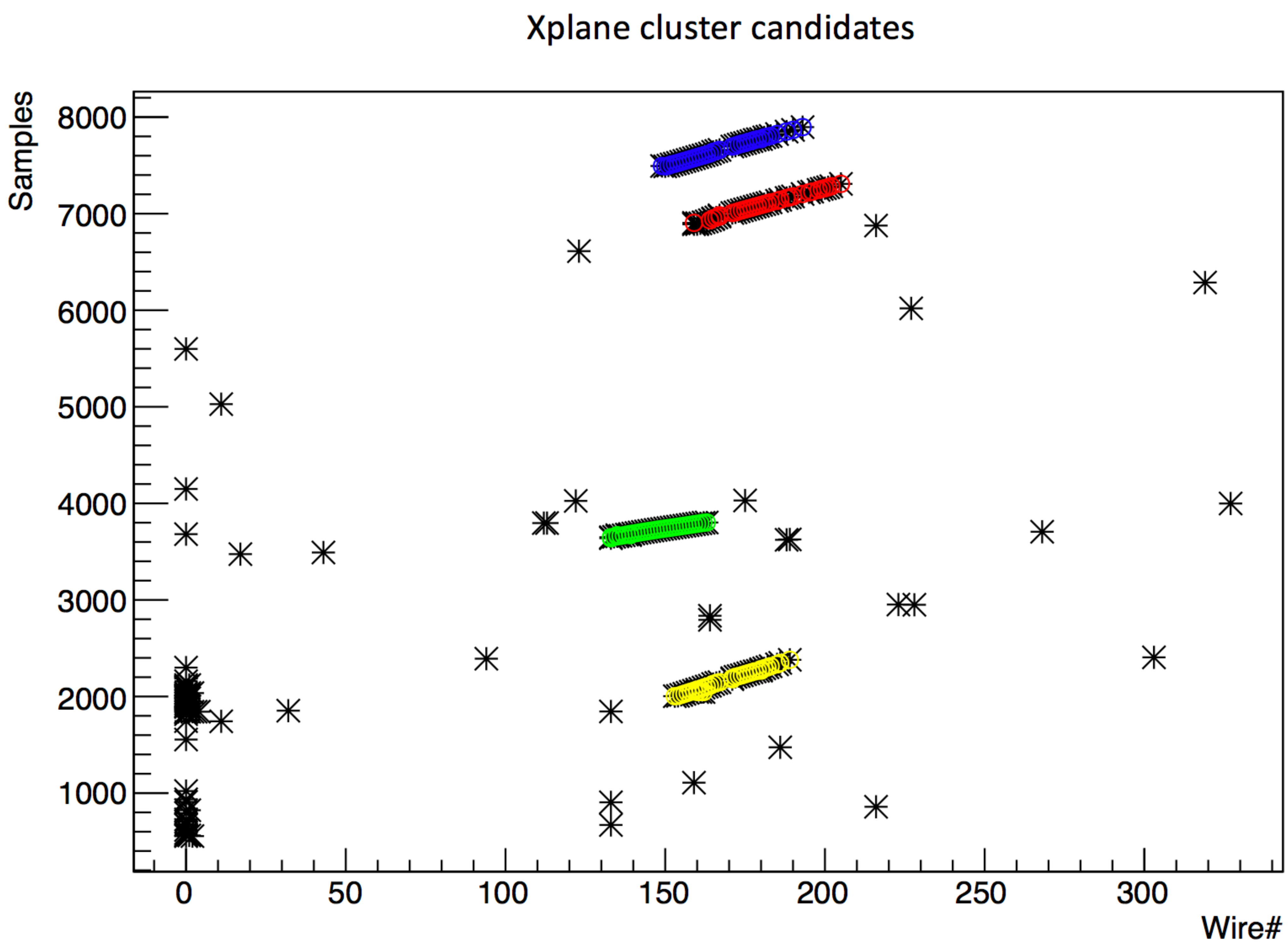
Reconstructing tracks





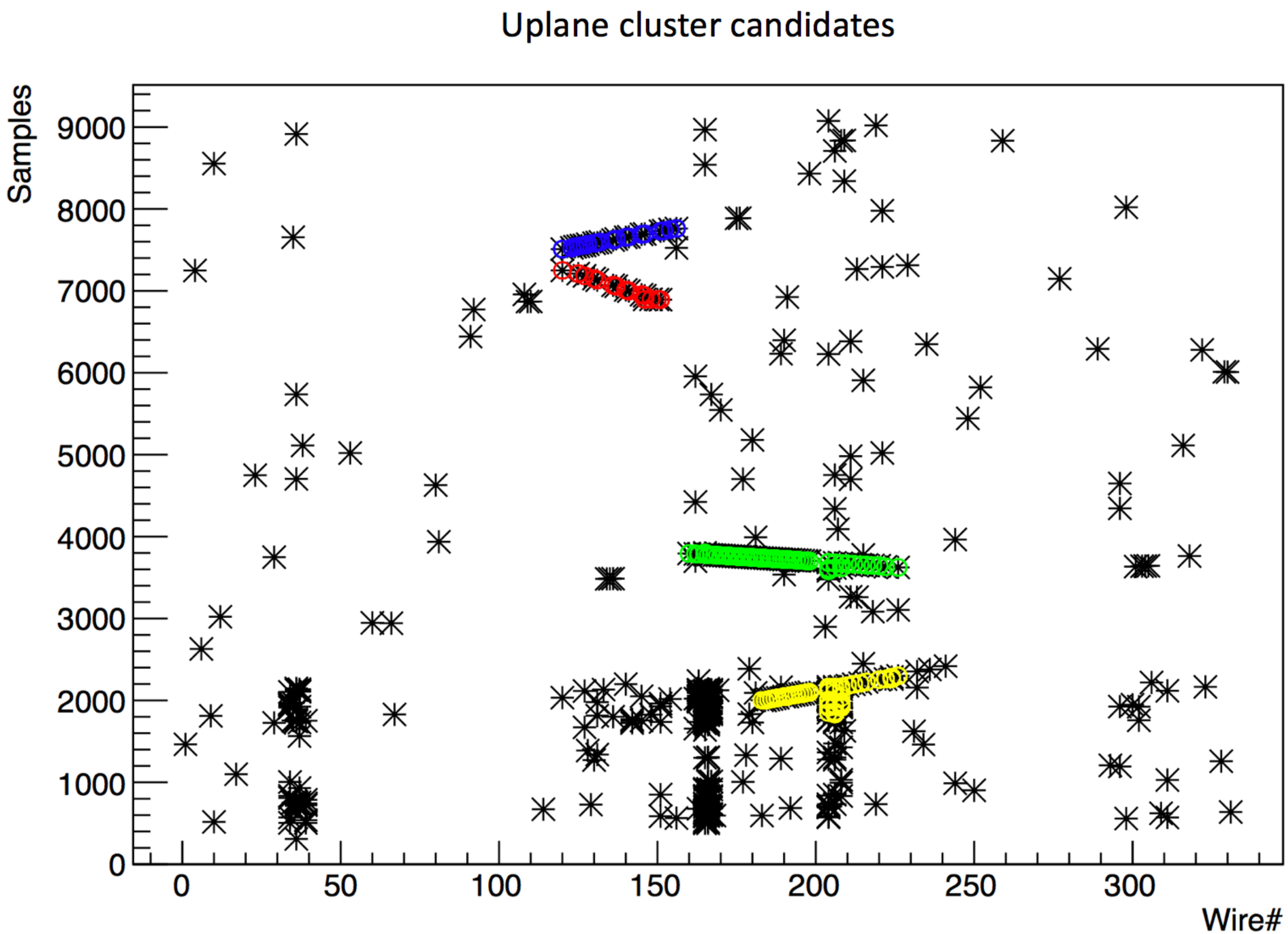
- Cleaning electrical signal from TPC
- Most of our track are fairly straight (protons and pions or cosmic muons)
- Use 2D Hough transform to find tracks
- Preliminary cluster: all hits within 4mm window around defined line.
- Pre-cluster is divided into objects if separated by more than 50mm.

Clustering



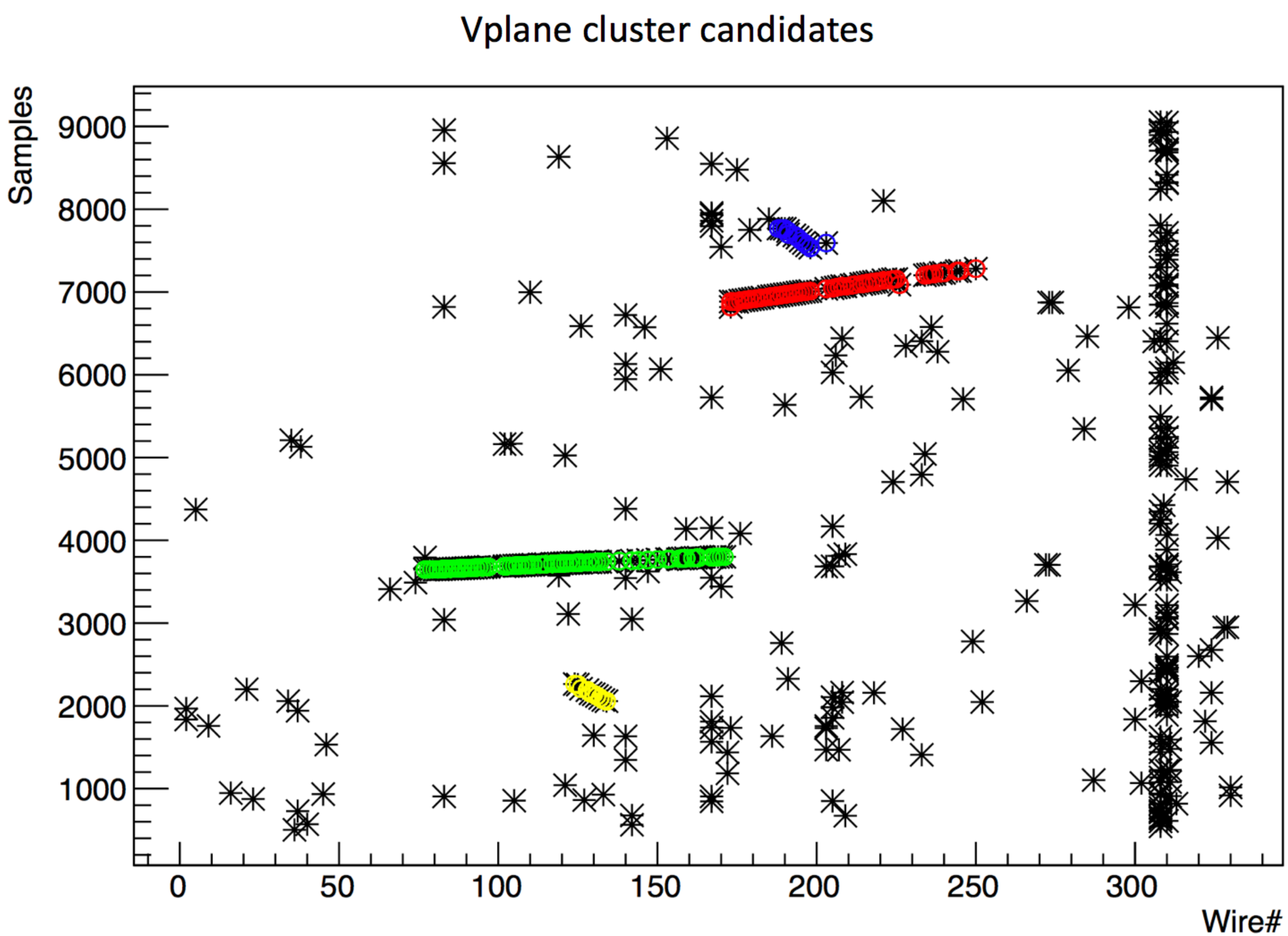
Xplane cluster candidates
Samples
8000
7000
6000
5000
4000
3000
2000
1000
0
50
100
150
200
250
300
Wire#

Clustering



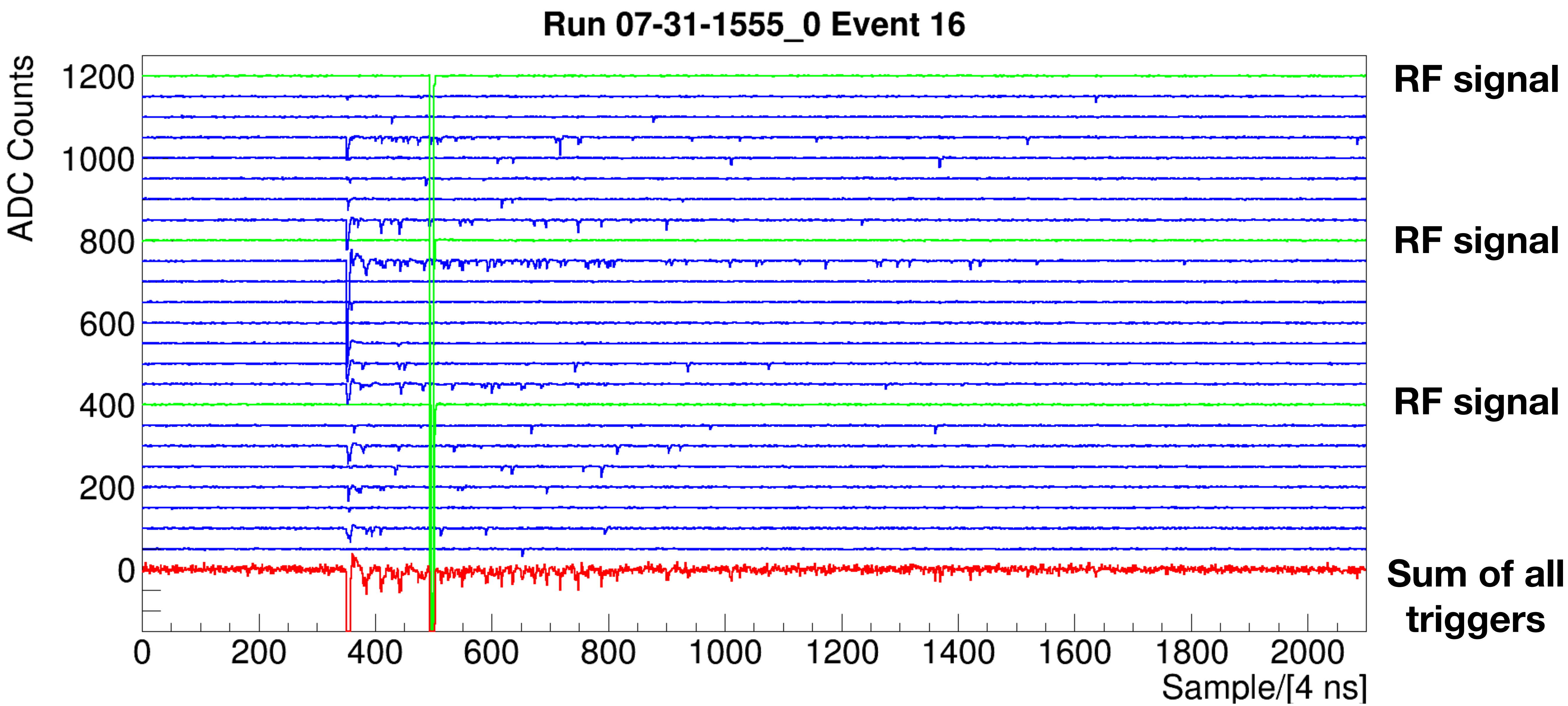
Uplane cluster candidates
Samples
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
Wire#

Clustering



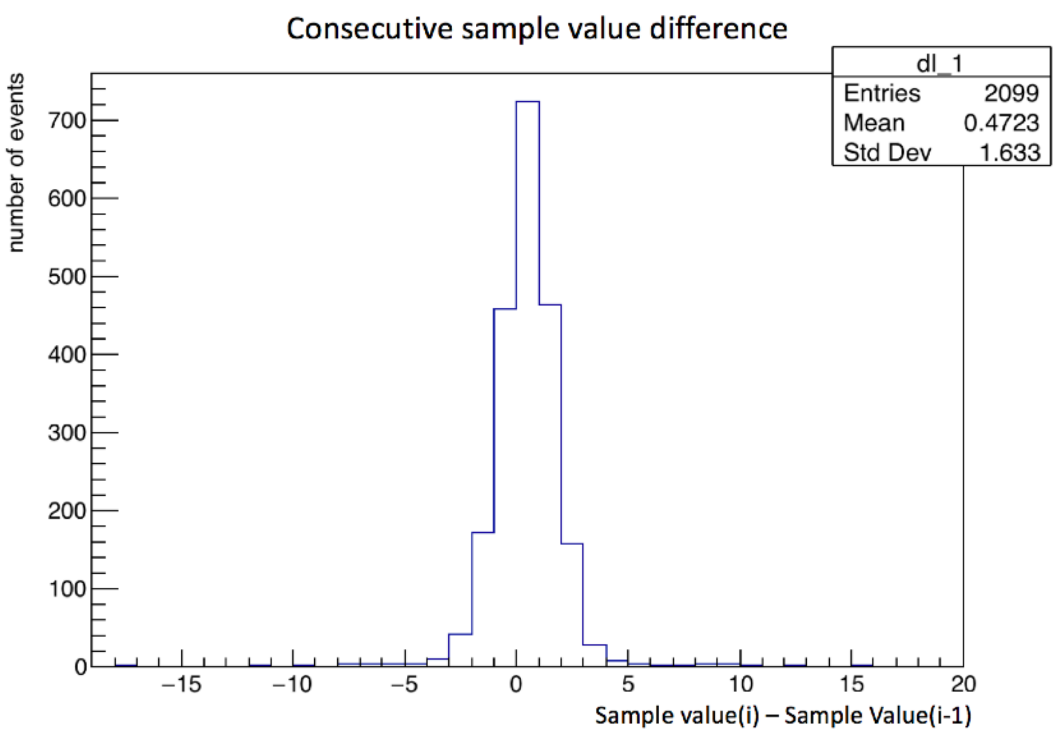
Vplane cluster candidates
Samples
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
50
100
150
200
250
300
Wire#

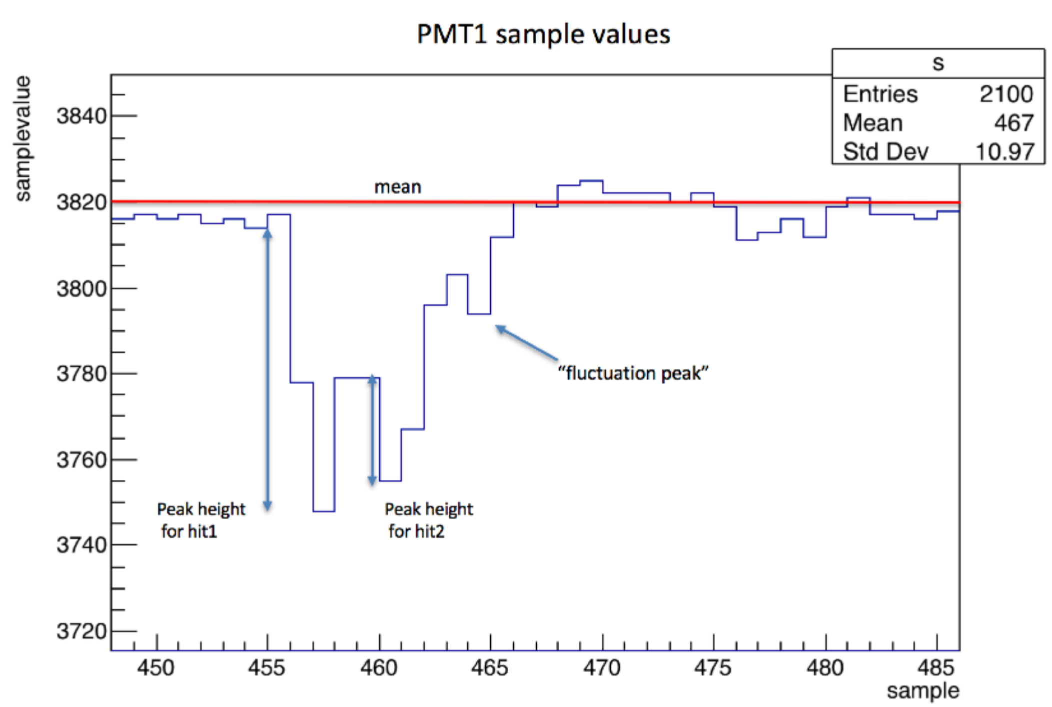
Photon triggers on PDS



- Triggering event during our low intensity run
- Each line corresponds to a single PMT

Making hits





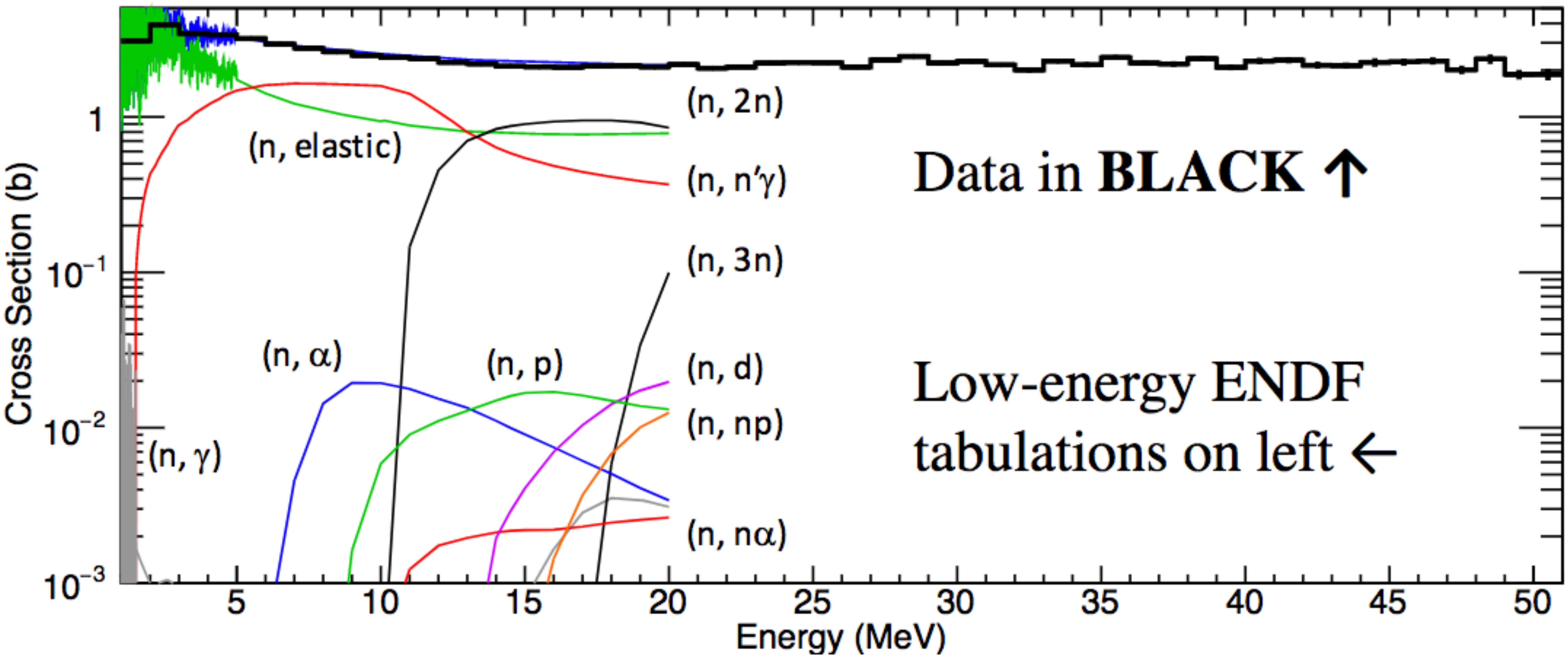
- All waveforms from PMTs are digitized
- PDS hits are defined as peaks above a baseline in the waveforms
    - Done independently for each PMT
- Hits are combined from all PMTs if they are close in time

Jorge Chaves

Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

Neutron cross section on LAr data available

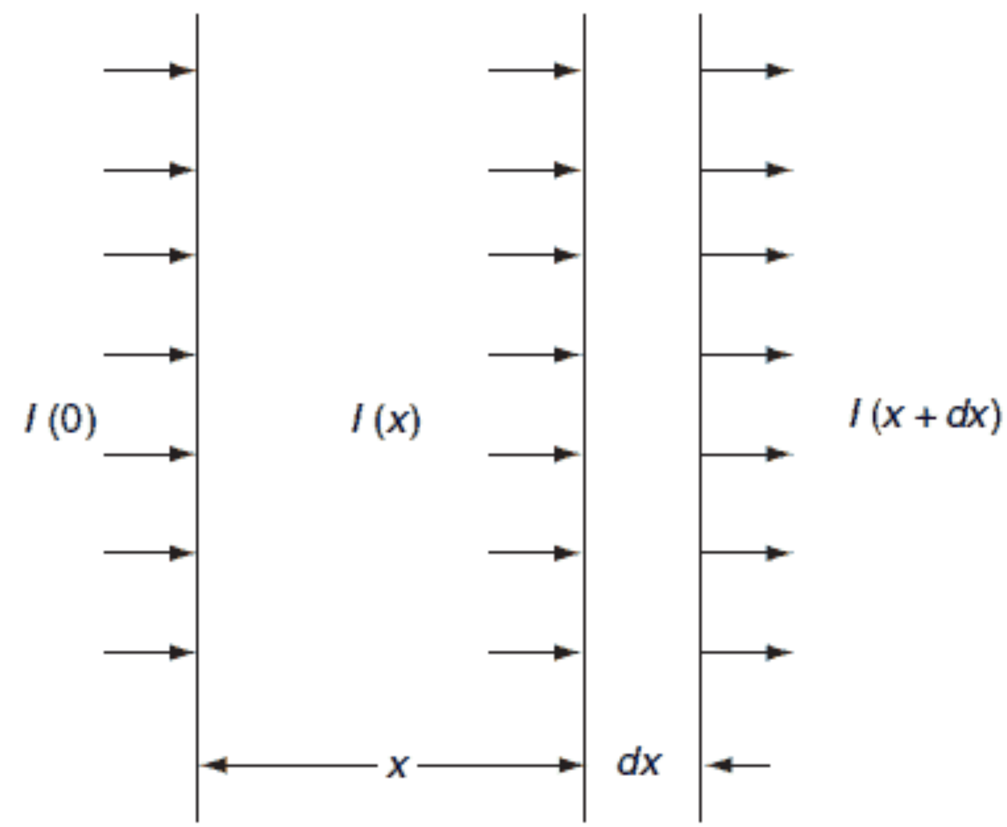


- Data is sparse at DUNE energies and existing data is from R.R. Winters et al., Phys. Rev. C43, 492 (1991) – www.nndc.bnl.gov

Jorge Chaves

Measuring the neutron cross section

- First result absolute inclusive cross section, followed by differential exclusive cross sections.
- Survival probability of neutrons decreases exponentially as a function of depth in detector and only depends on cross section and target density.
- For a chosen event topology, fit an exponential to the starting positions of the tracks and you get the cross section.
  - In our case, the topology is single track events.
- Data binned in energy bins where cross section doesn't change as much.

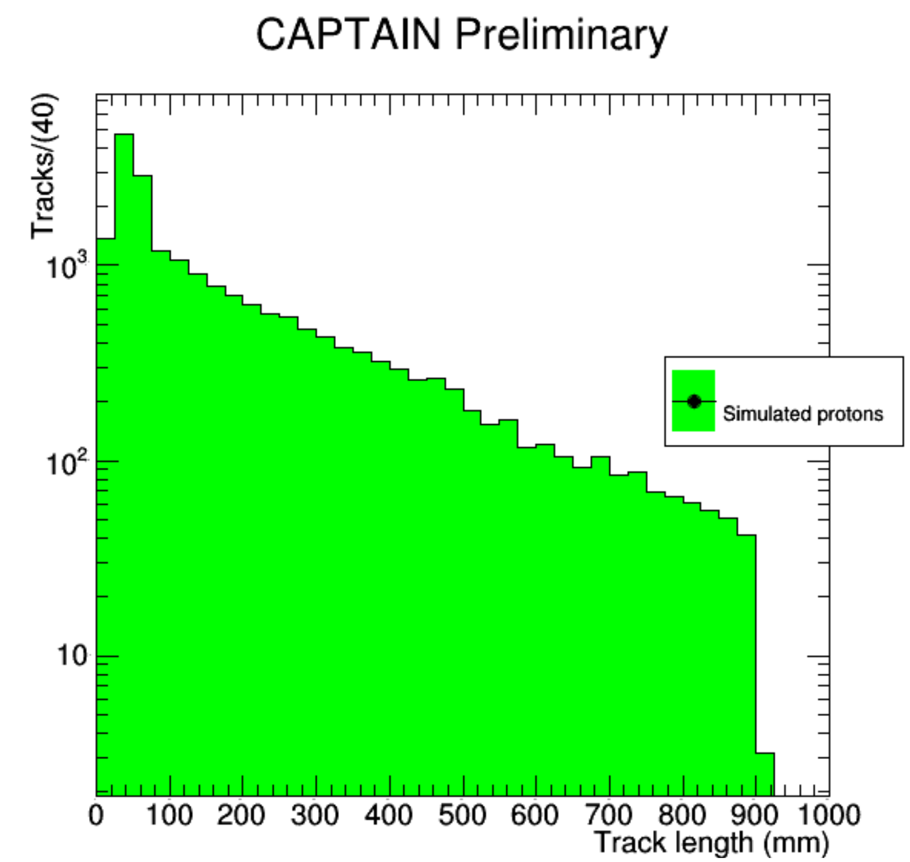


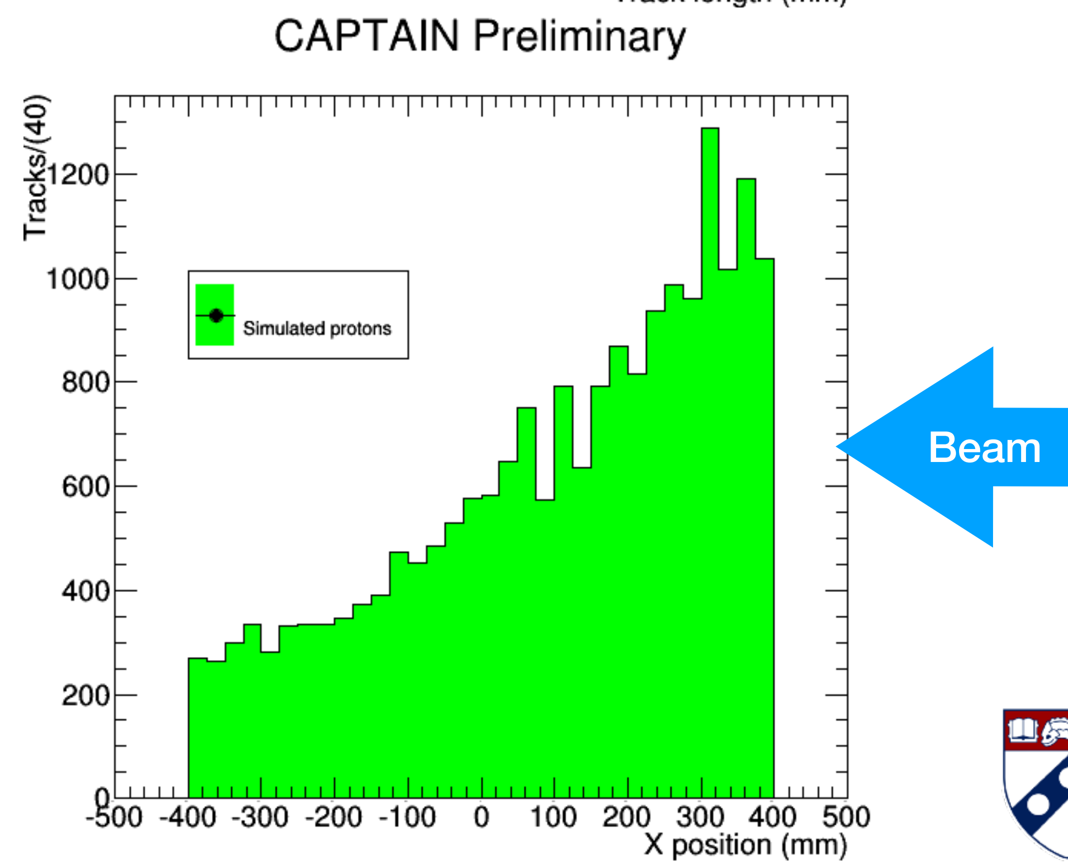
$$I(x) = I_0 e^{-N\sigma x}$$

N = atomic density of Argon

MC simulation

- A large sample of protons was simulated over a broad range of track lengths.
    - Actual track length distribution in data is not known a priori.
- Use this simulation to study reconstruction efficiency.
- Top: Reconstructed track length of simulated protons.
- Bottom: Starting x position of reconstructed tracks.

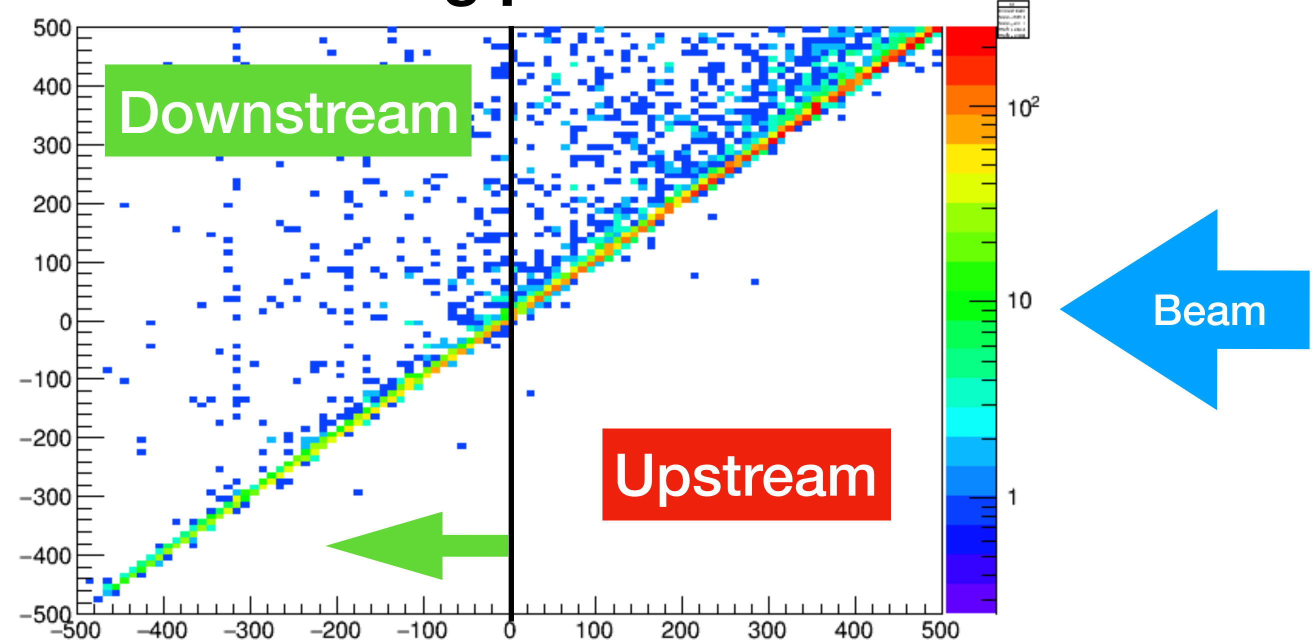




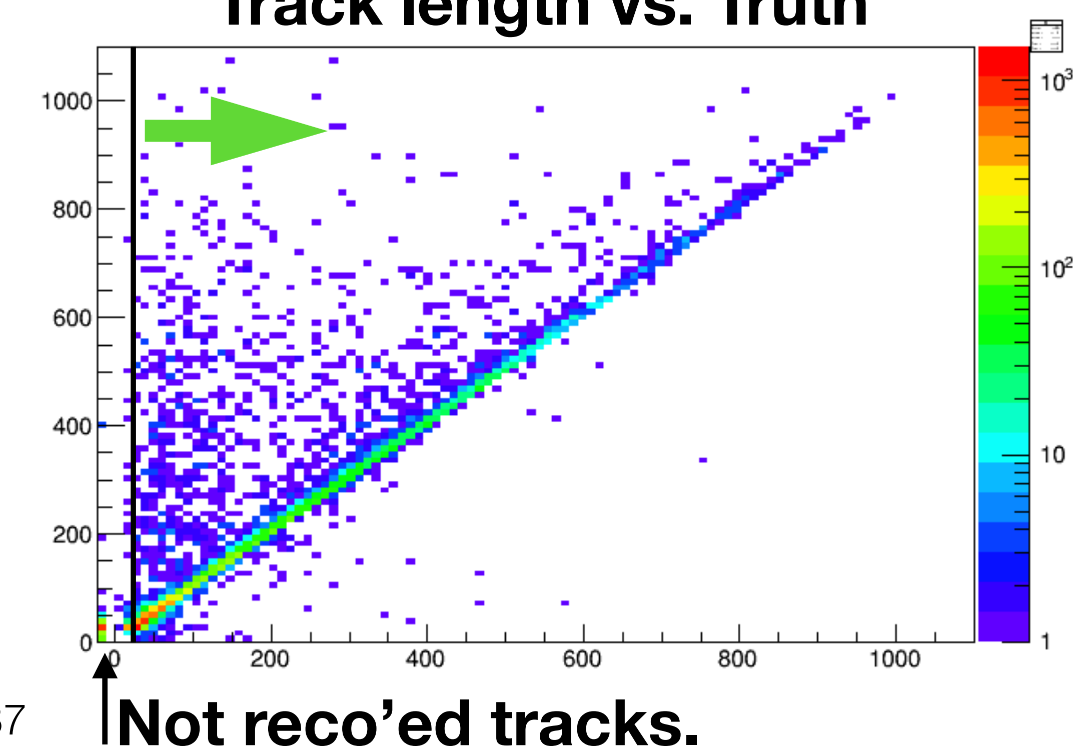
Fiducial volume and quality cuts

- We are considering only using the downstream of the detector to avoid the wire inefficient seen upstream.
  - Further studies are under way to understand the effect of this inefficiency.
- Very short tracks are not reconstructed by our algorithm.
  - Cut tracks shorter than 35 mm.
  - No tracks below 60 MeV.
- Track reconstruction with in-house algorithm. Not using LArSoft.

Track X starting position vs. Truth

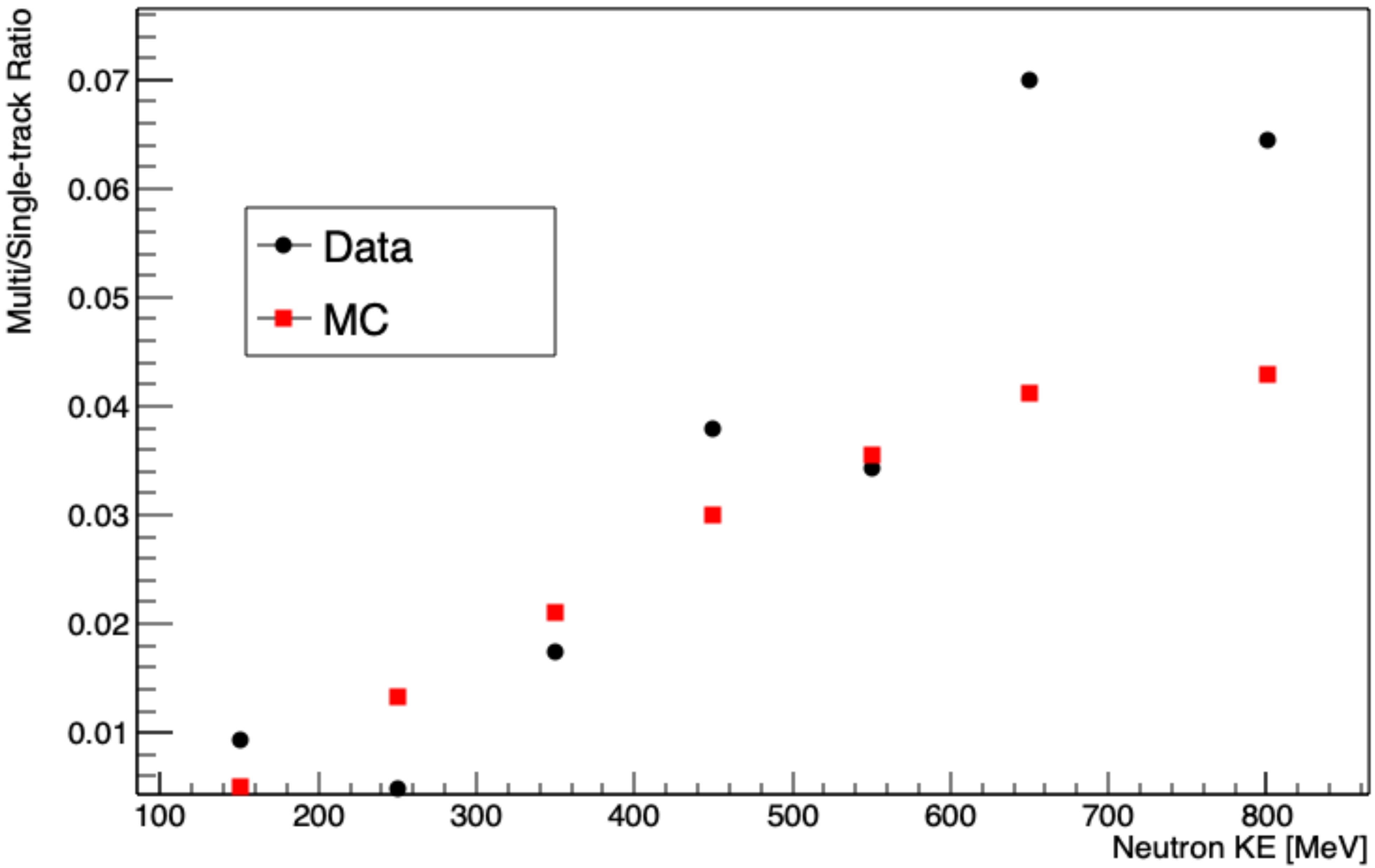


Track length vs. Truth



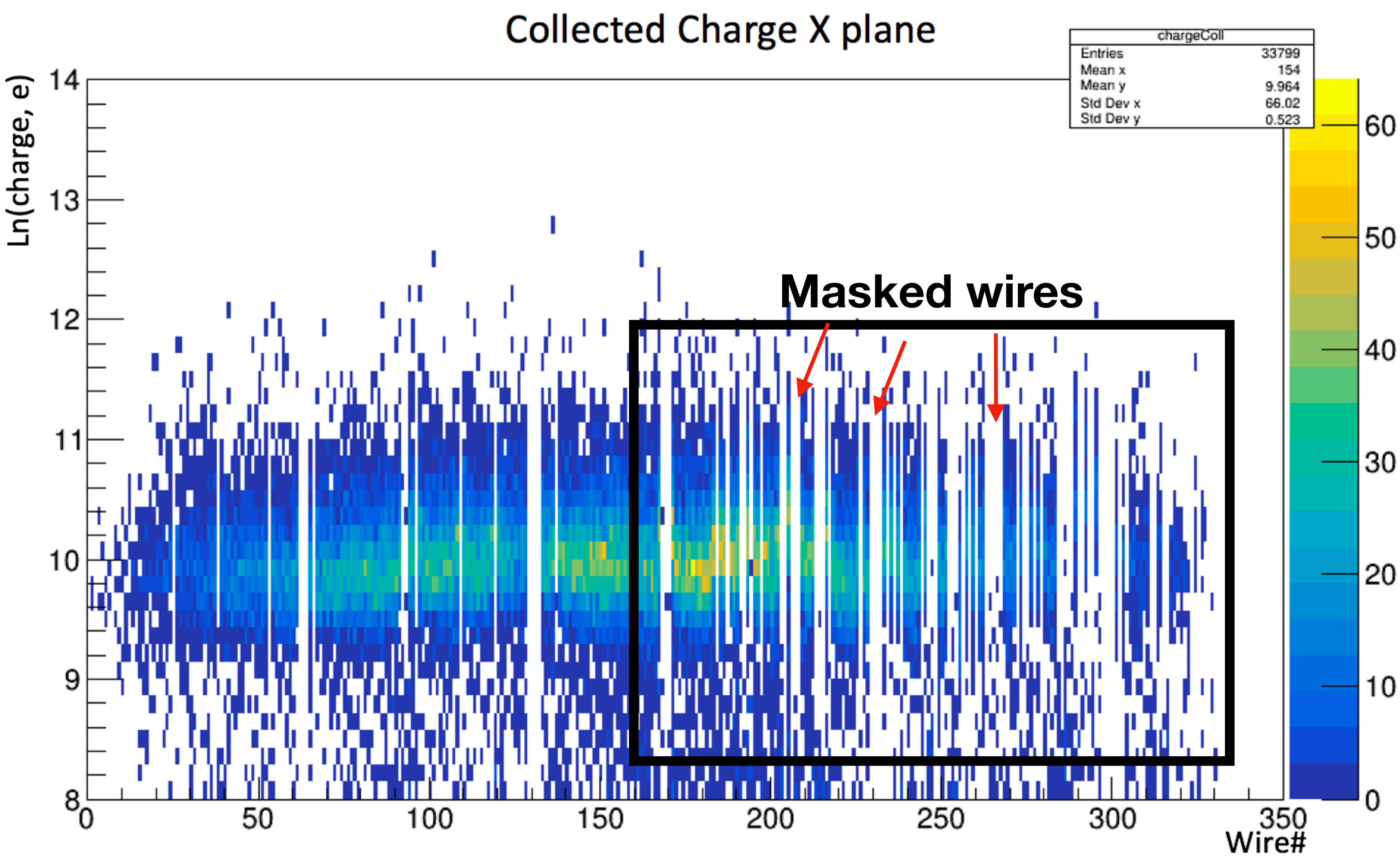
Jorge Chaves

Multi-track events



- Simulation predicts at most a change of 10% in the cross section due to multi-track events

Hit-finding efficiency



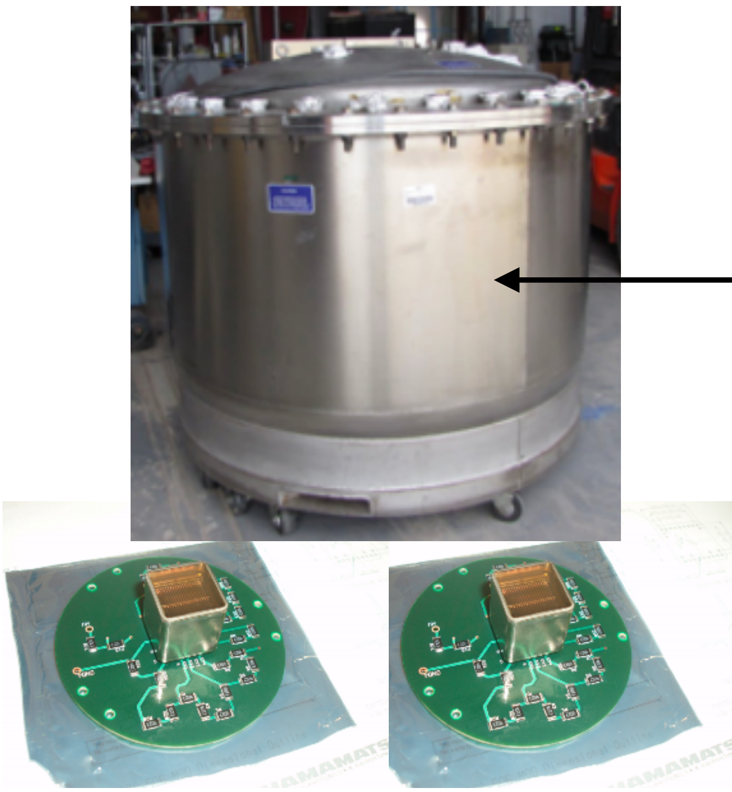
- Hit finding inefficiency seen upstream of the detector
- Most likely caused by unresponsive wires -> only consider tracks in the downstream of the detector

Jorge Chaves

Neutron kinetic energy

- The photon detection system provides an independent measure of the neutron kinetic energy based on time-of-flight measurements.
- TPC and PDS data stored in separate streams and have been matched.
- For every reconstructed track we can assign a kinetic energy for the neutron that created it.
- The exponential fits to extract the cross section can then be done as function of the neutron kinetic energy.

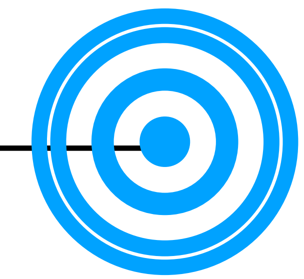
Measuring the neutron KE



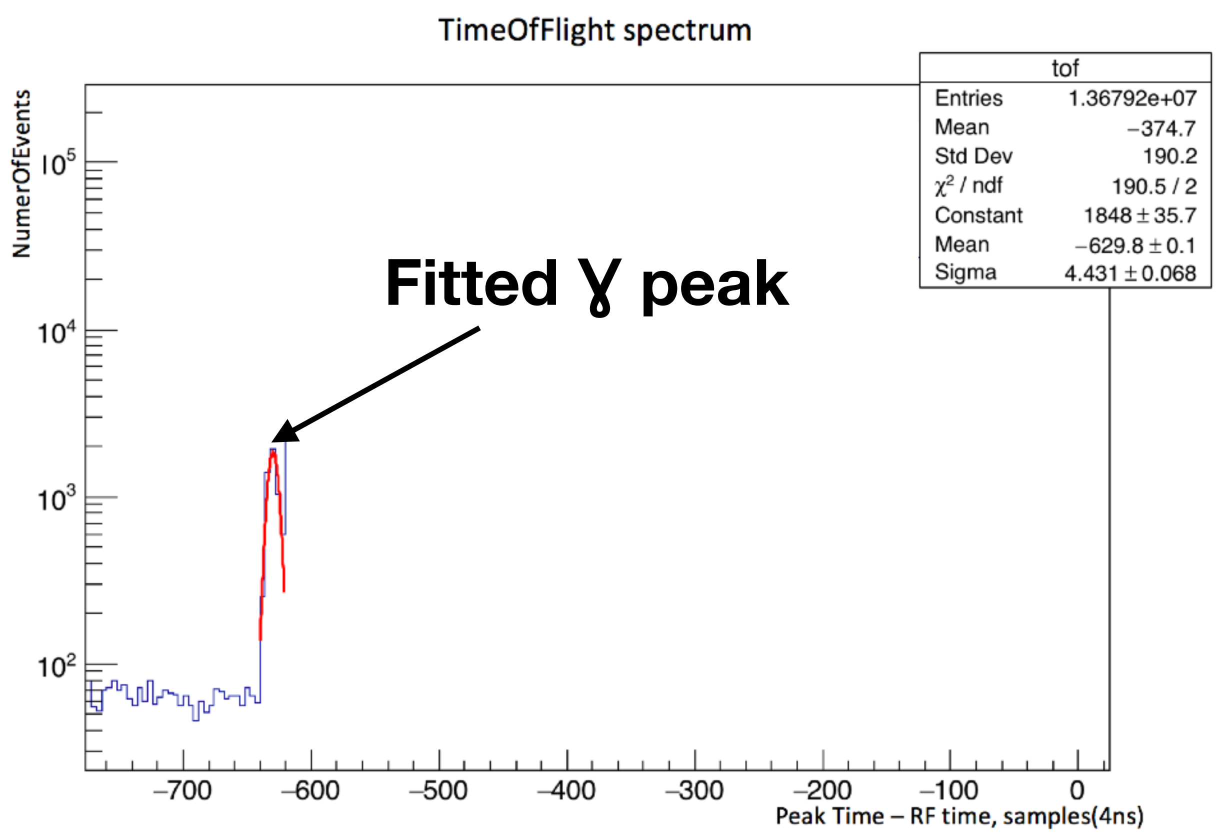
Hamamatsu R8520-506
PMTs

γ

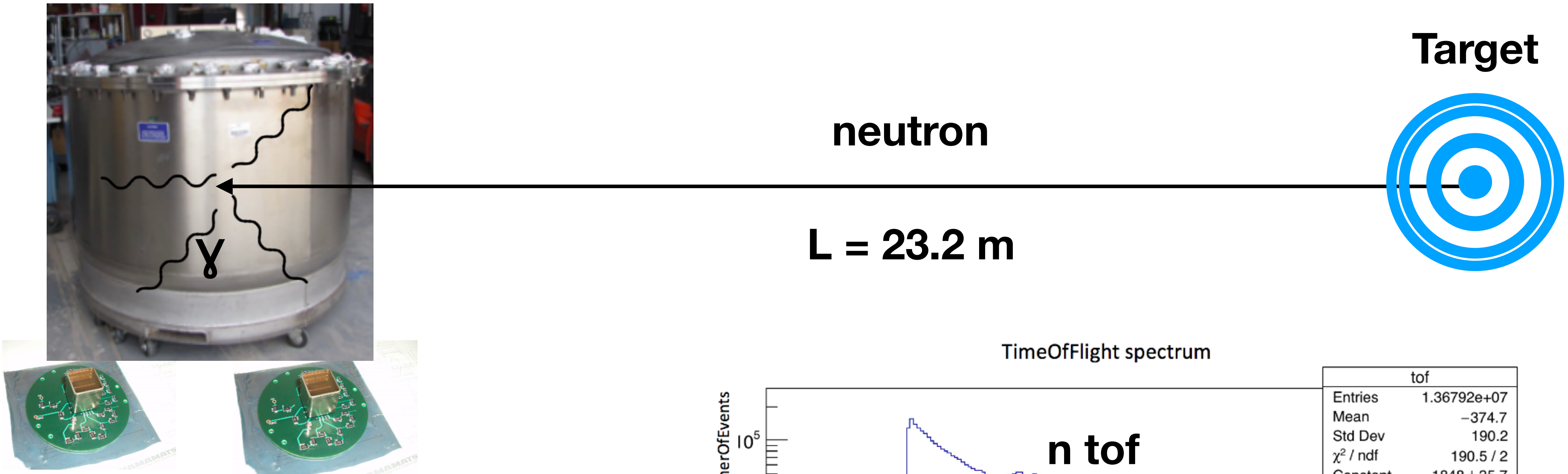
Target



L = 23.2 m



Measuring the neutron KE

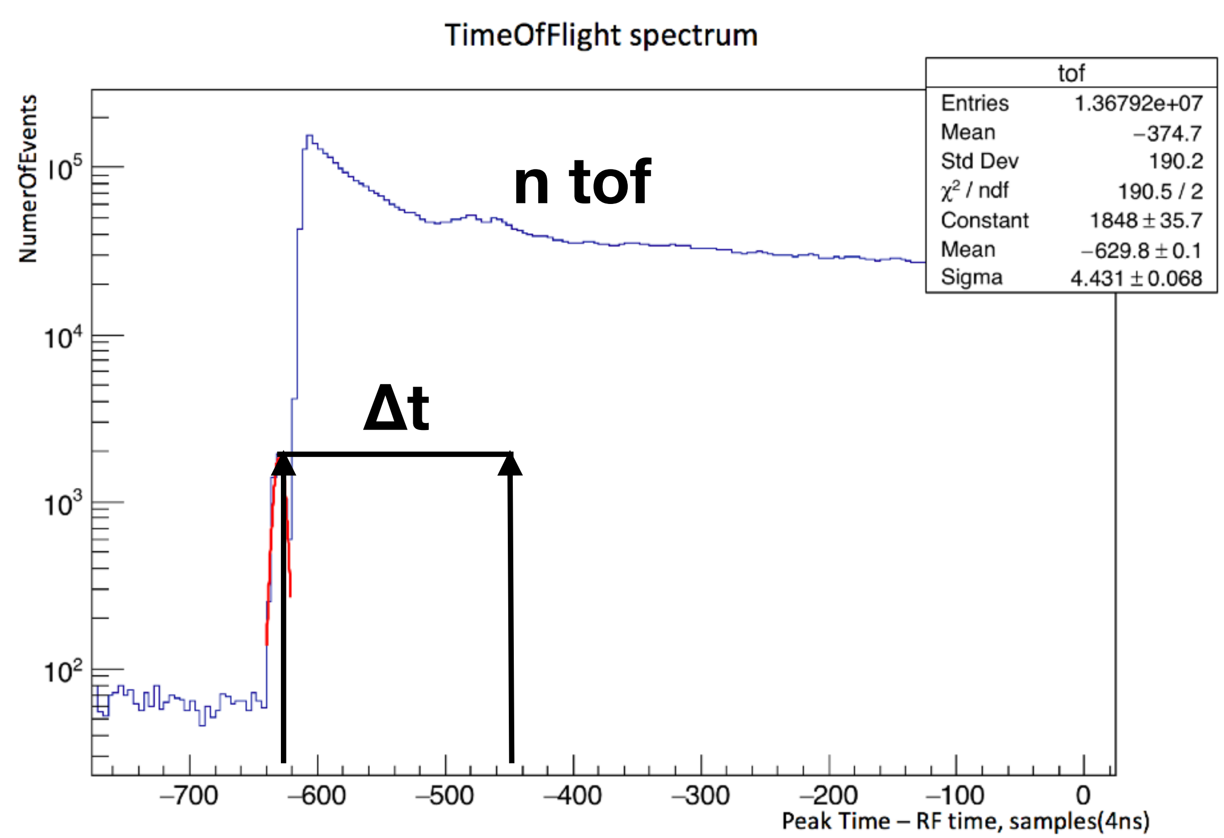


$$t = (\Delta t) + L/c$$

$$p = \frac{m_n L}{\sqrt{c^2 \Delta t^2 - L^2}}$$

$$KE_n = \sqrt{p^2 + m_n^2} - m$$

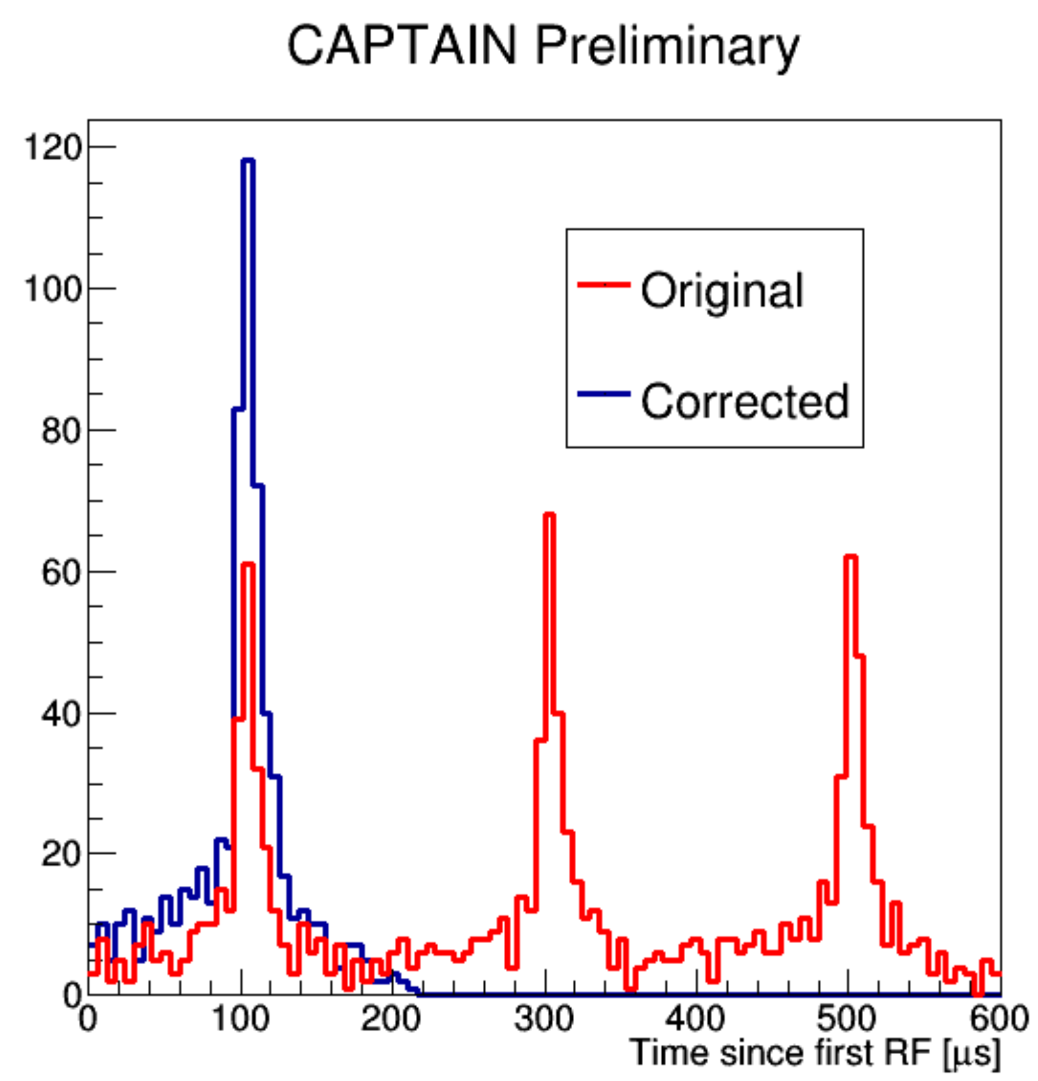
Neutron KE calculated only using the PDS



Jorge Chaves

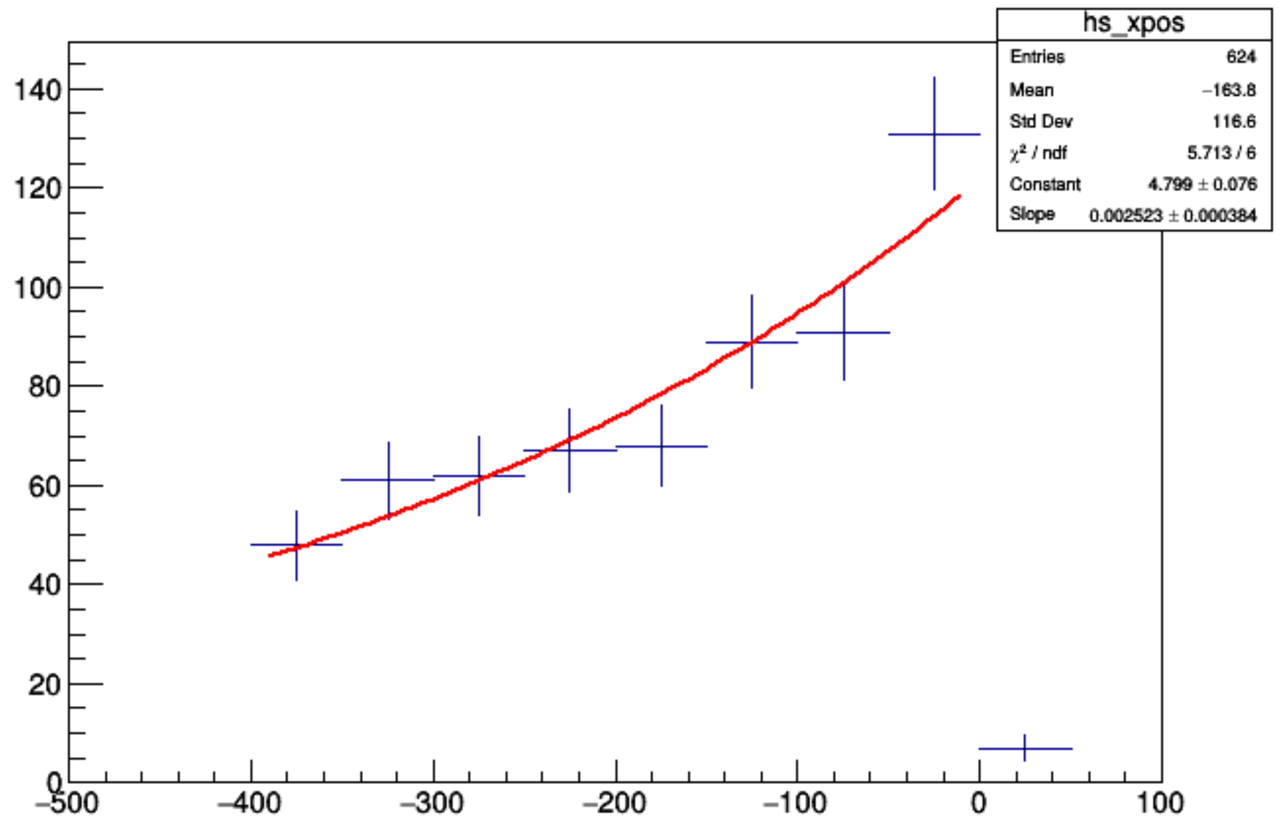
TPC/PDS matching

- Beam structure of 3 micro pulses within the TPC acquisition window.
- Neutrons appear to arrive much later with respect to first trigger.
- Information from the PDS can help correct the timing of the tracks.
- Currently the efficiency to correctly match tracks to PDS events is > 95%.
    - Working on understanding the correct neutron energy assignment based on TOF.
- If energy assignment efficiency is on par with the matching, we expect a very small systematic from this.



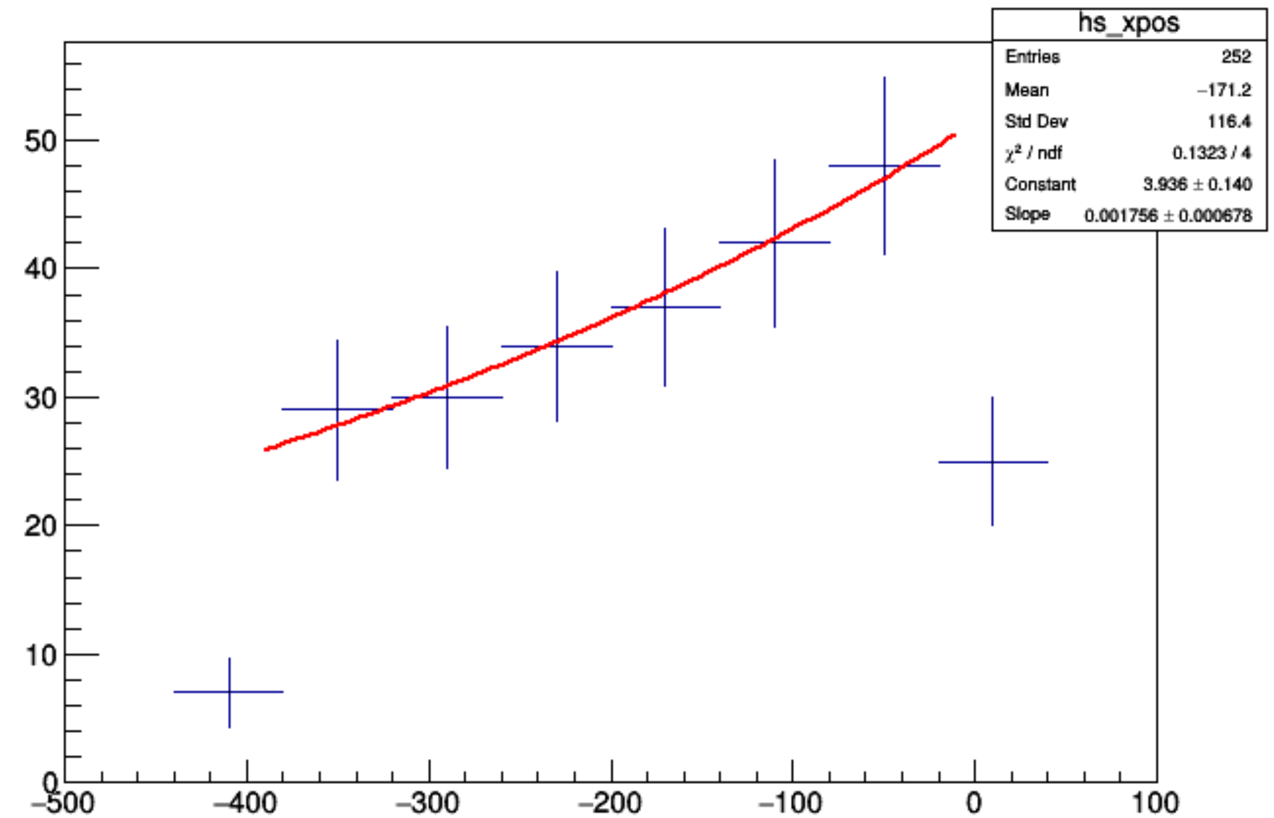
Cross section fit

481-674 MeV



X position [mm]

674-900 MeV

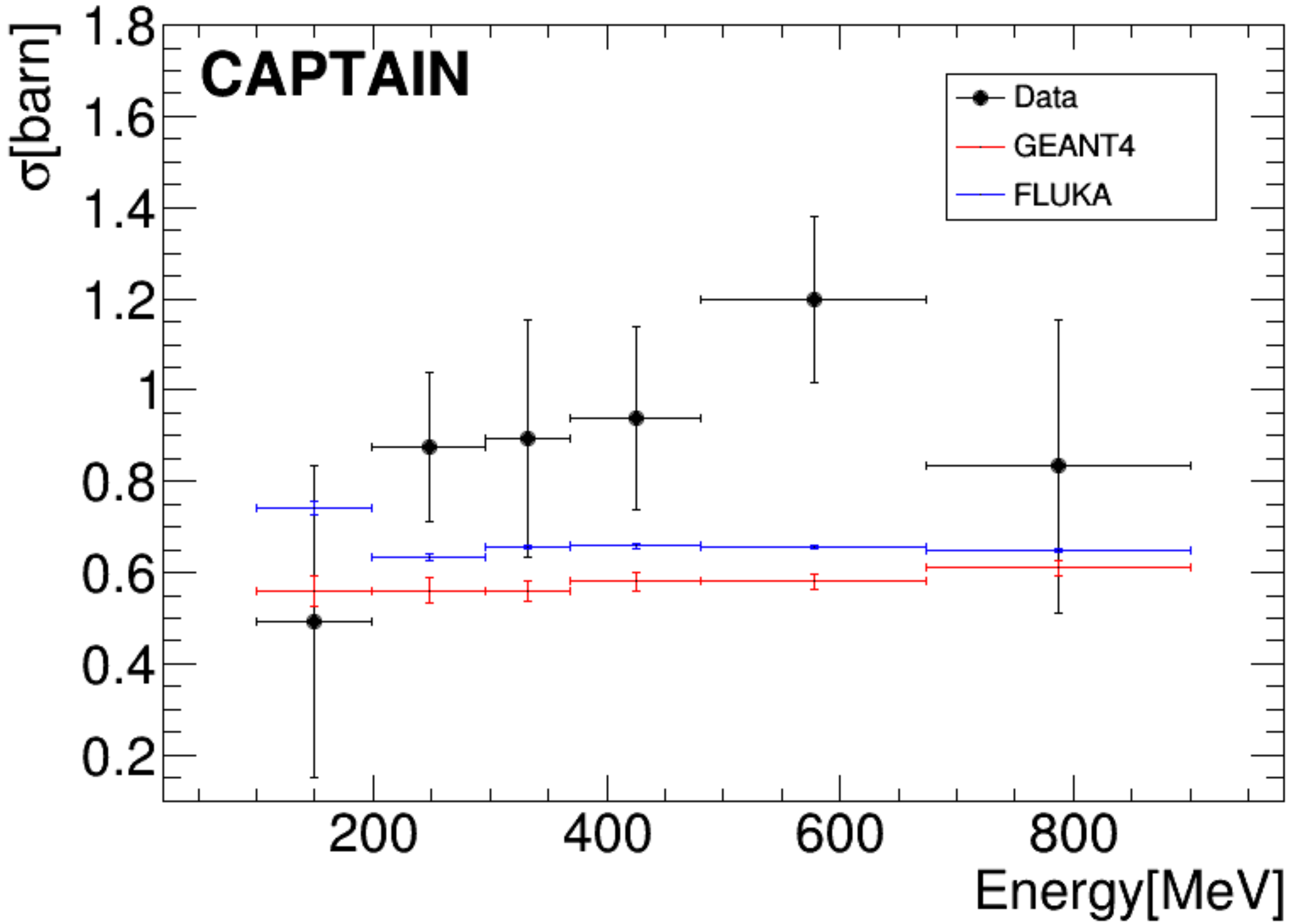


X position [mm]

- For a given energy, the total cross section is proportional to the exponential coefficient of the neutron flux depletion rate for a given topology
- Exponential fits with binning based on available statistics

Neutron cross sections

arXiv:1903.05276



Jorge Chaves

Neutron cross sections

Energy range [MeV]	Cross Section [barns]	χ^2/ndof	Number of tracks
100-199	0.49±0.34	1.48/3	264
199-296	0.88±0.16	11.81/7	536
296-369	0.89±0.26	4.739/5	329
369-481	0.94±0.20	8.262/6	413
481-674	1.20±0.18	5.713/6	624
674-900	0.83±0.32	0.1323/4	252

- Fits are reasonable given the available statistics
- Last bin chi2 is small -> probability of data consistent with an exponential distribution is 0.998
- Cross section energy-weighted average is 0.91±0.10(stat)±0.09(sys) barns

Outline

- Introduction and motivation
- Experimental setup
- Analysis strategy
- Status and future plans

Present status: Neutron measurements with Mini-CAPTAIN

- Understanding high-energy neutron interactions in a LAr-TPC is an obvious goal of Mini-CAPTAIN
    - Additional physics analyses ongoing with neutron data taken at Los Alamos WNR.
- Absolute cross section result paper submitted to PRL.
- Differential cross sections to follow by implementing particle identification.
- Current uncertainties dominated by statistics. Working on understanding the data in the detector upstream. Triple our dataset.
- Propagate the results and compare with current models.

Looking to the future: Neutrino cross sections with CAPTAIN

- An important goal of DUNE is to be able to detect supernova neutrinos.
  - We need to understand what the detector response/efficiency should be.
- CAPTAIN is a fairly sized LArTPC that can provide some insight into these requirements before DUNE is built
  - Possibly deployed at the Spallation Neutron Source (SNS) at Oak Ridge.
- In addition, the CC/NC cross sections of low energy neutrinos have not been measured in Argon.
- CAPTAIN detector can serve as a testbed for some of the technology needed for a large TPC, but it is also more flexible when it comes to where it can be located.

Summary

- Understanding neutron interactions with Argon is crucial for an accurate reconstruction of neutrino energy.
  - Specially important for the measurements that DUNE wants to do.
- Mini-CAPTAIN physics run last summer was a success and a neutron cross section measurement is in the works.
- The CAPTAIN run plan includes improved and additional measurements:
  - Low energy neutrino cross sections

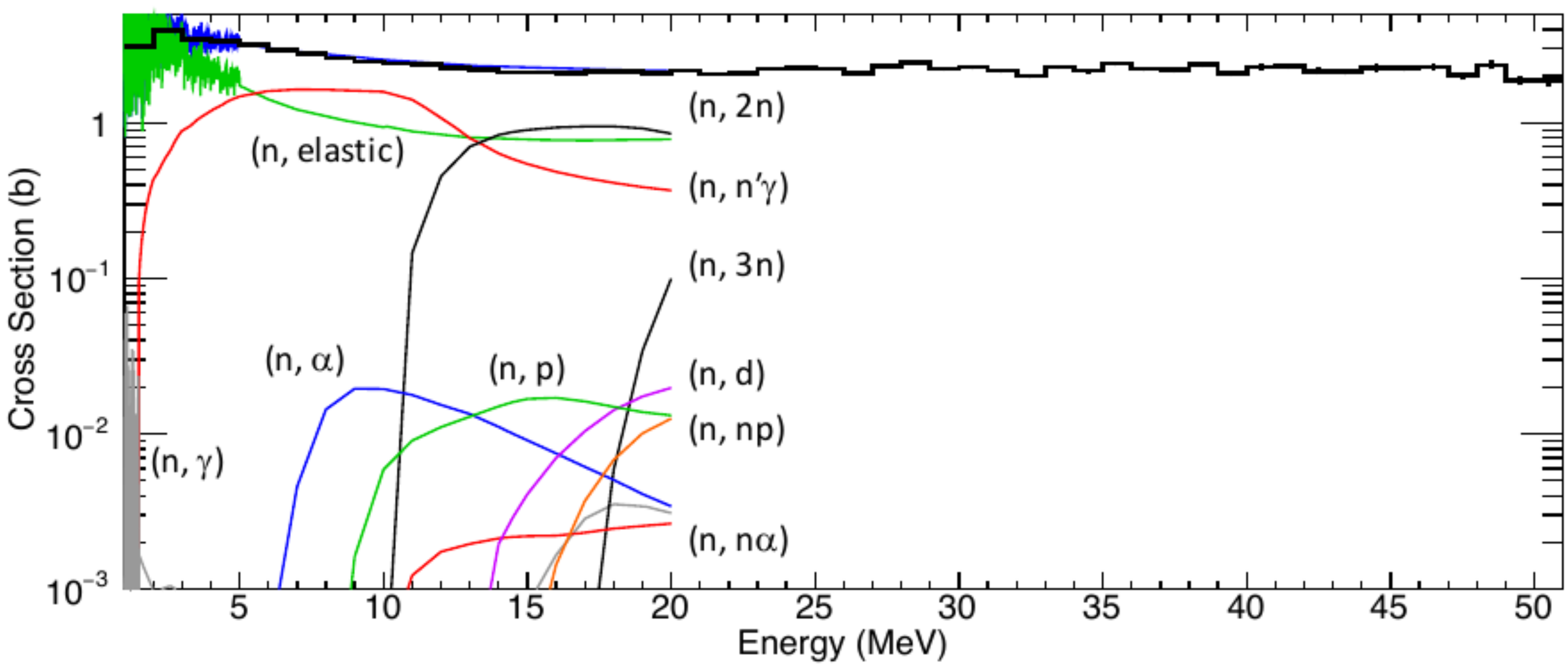
CAPTAIN collaboration

- Picture from the physics run this summer in front of MiniCAPTAIN in the WNR flight path at LANSCE.

BACKUP

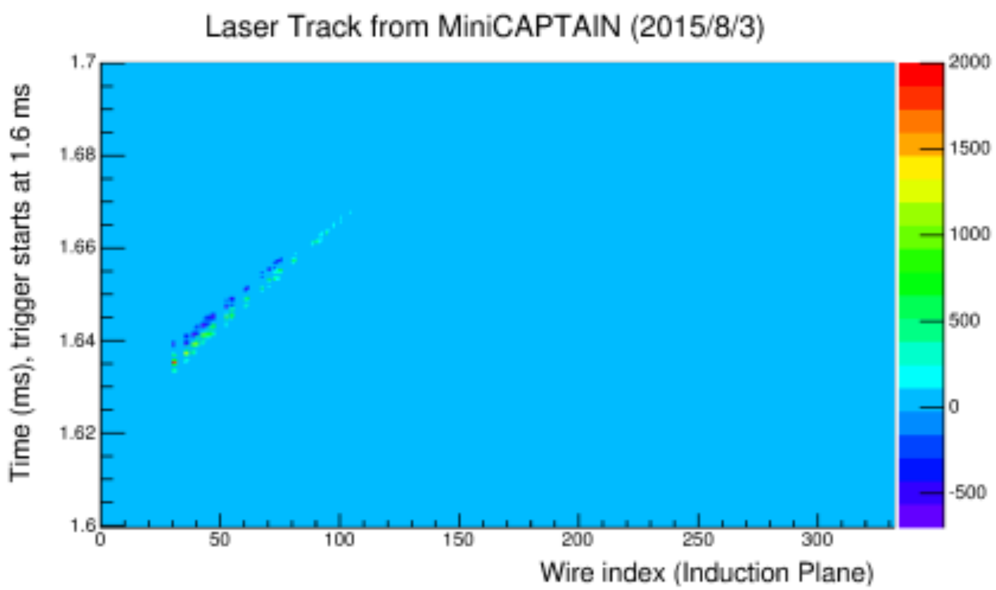
Neutron Cross-Sections on Argon

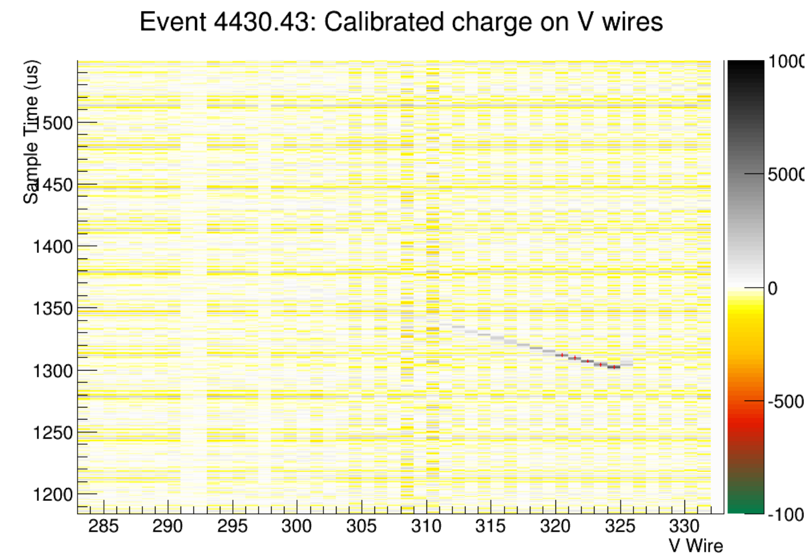
R.R. Winters et al., Phys Rev C 43, 492 (1991) – nndc.bnl.gov

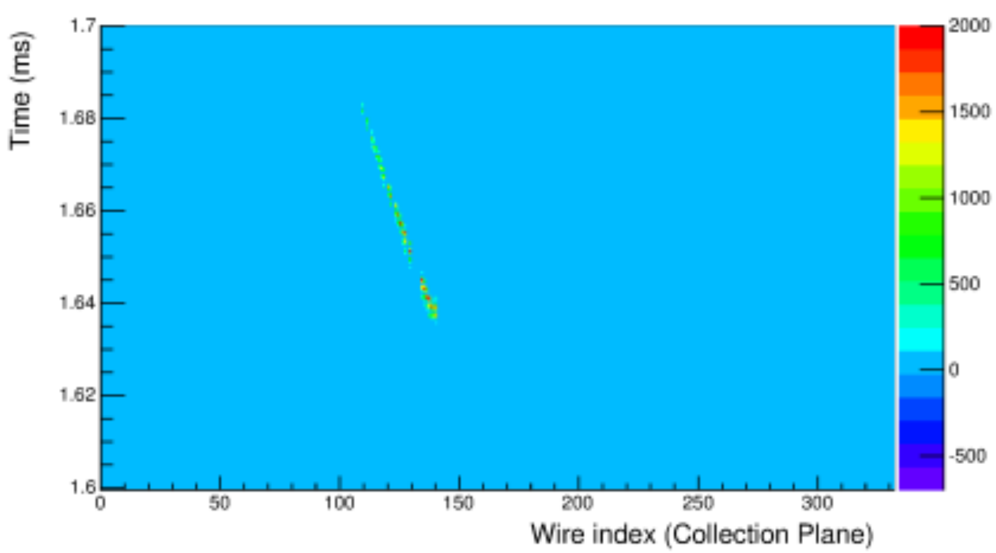


Jorge Chaves

First signals in miniCAPTAIN



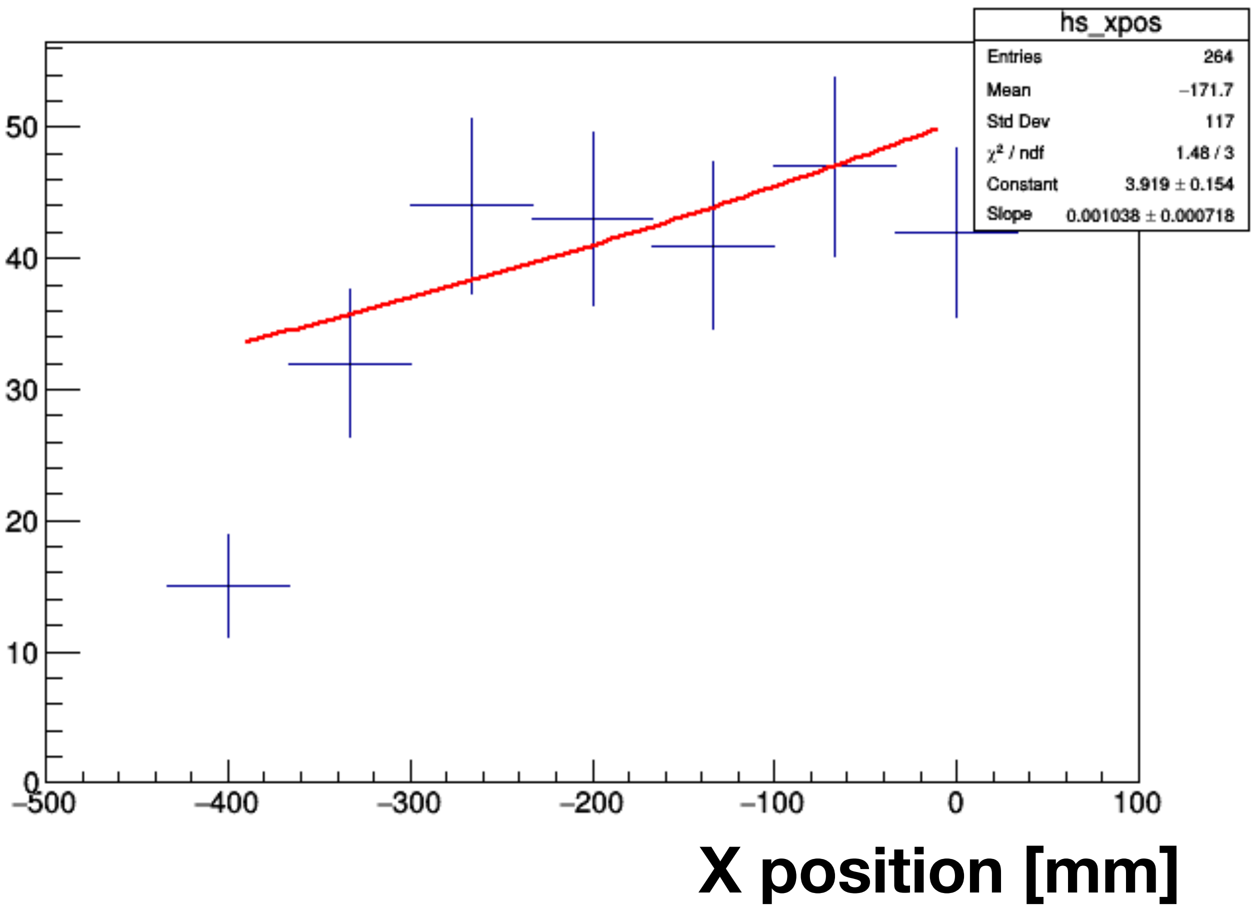




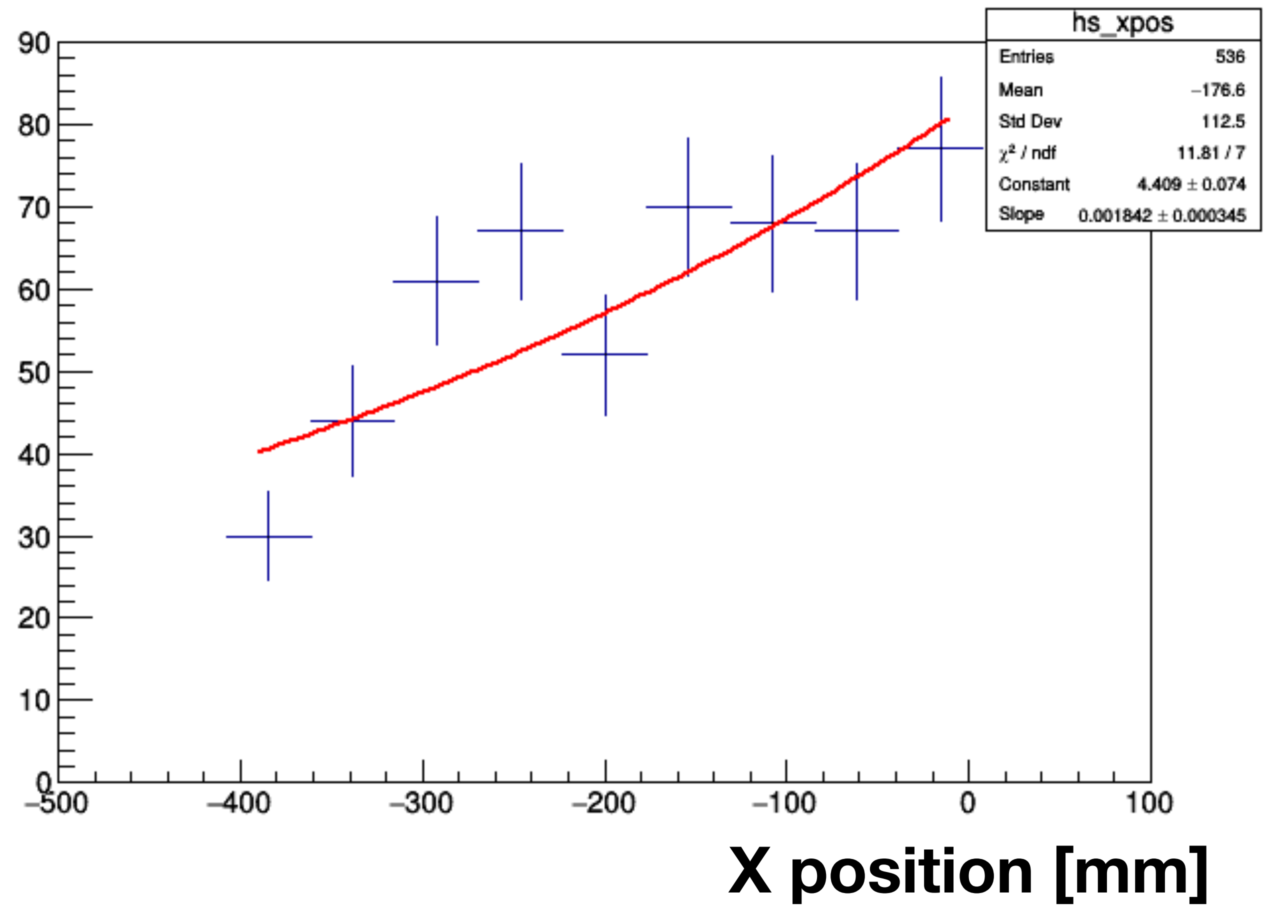
- First drift signals collected during summer 2015 commissioning
  - Electron lifetime was ~20μs w/o indium seal to ease access to TPC (will add for physics run)

Cross section fit

100-199 MeV



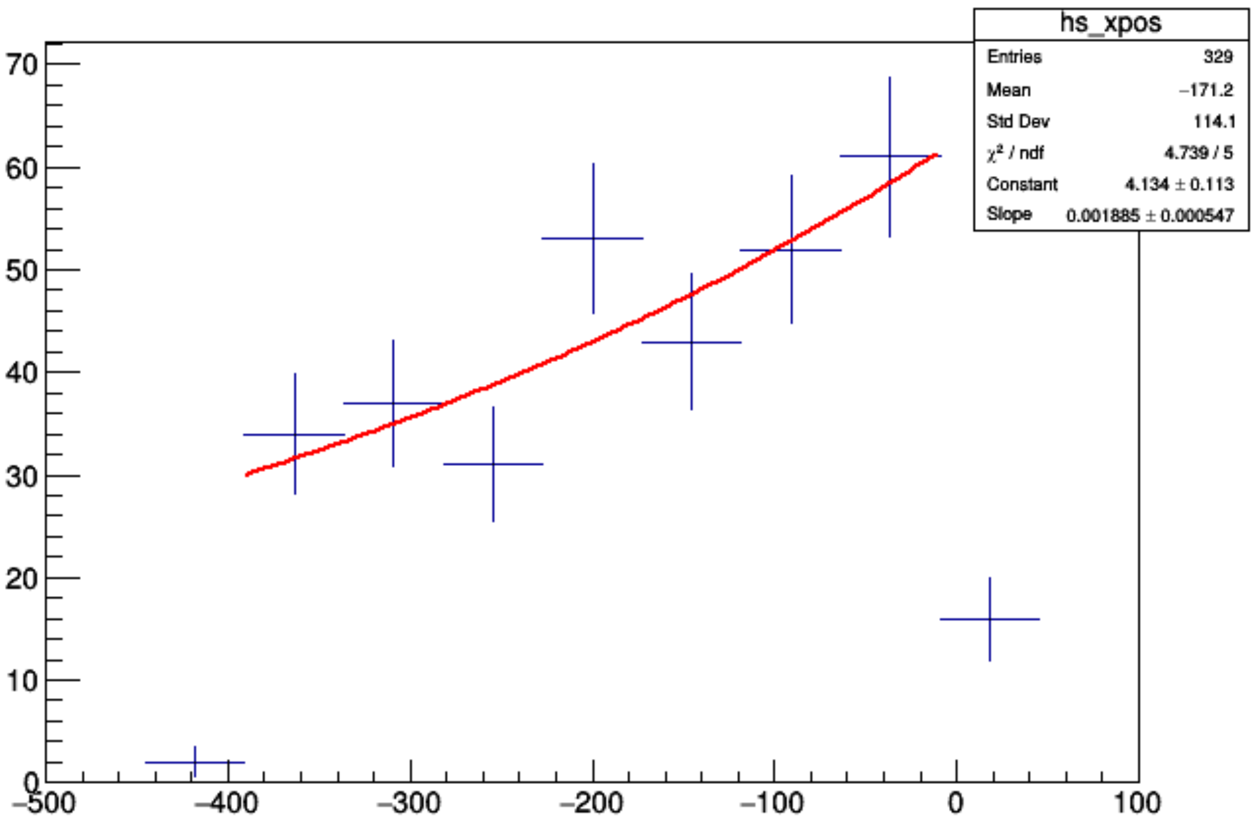
199-296 MeV



Jorge Chaves

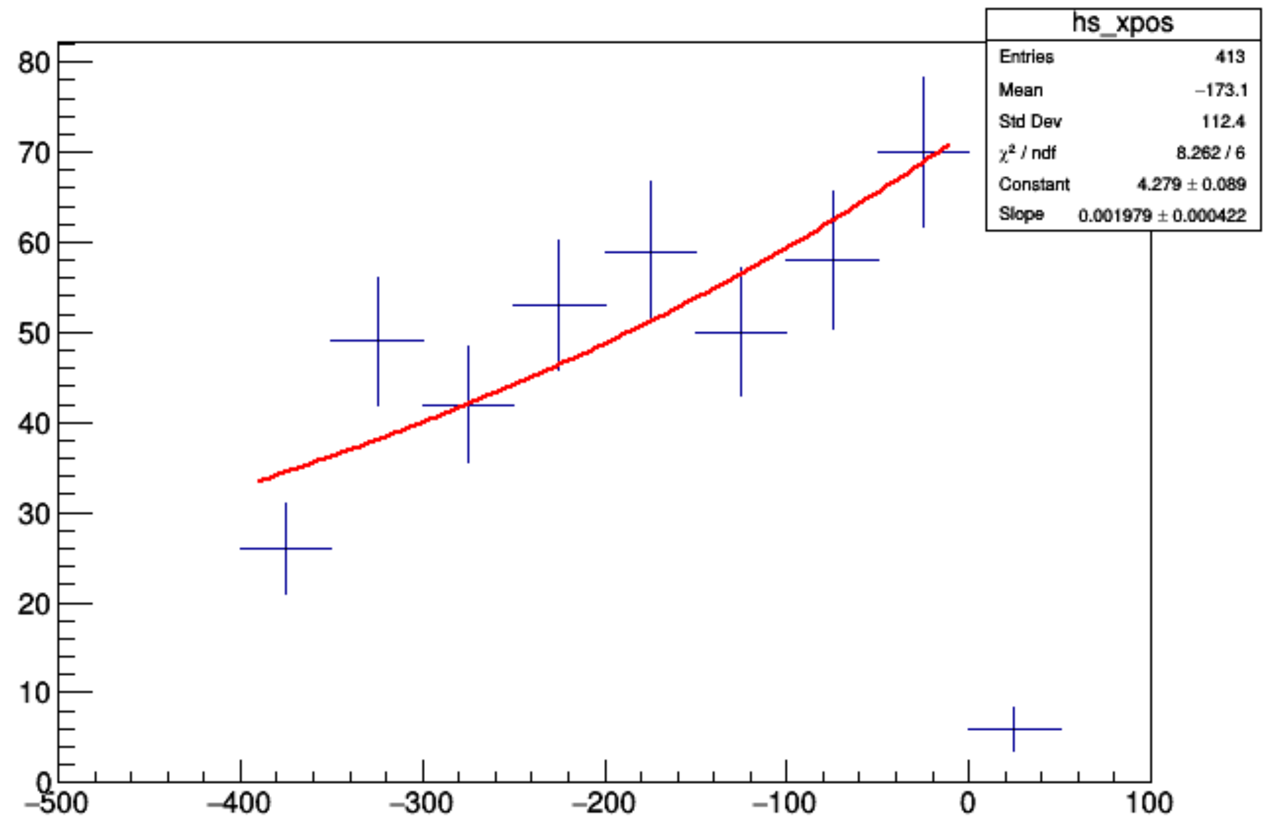
Cross section fit

296-369 MeV



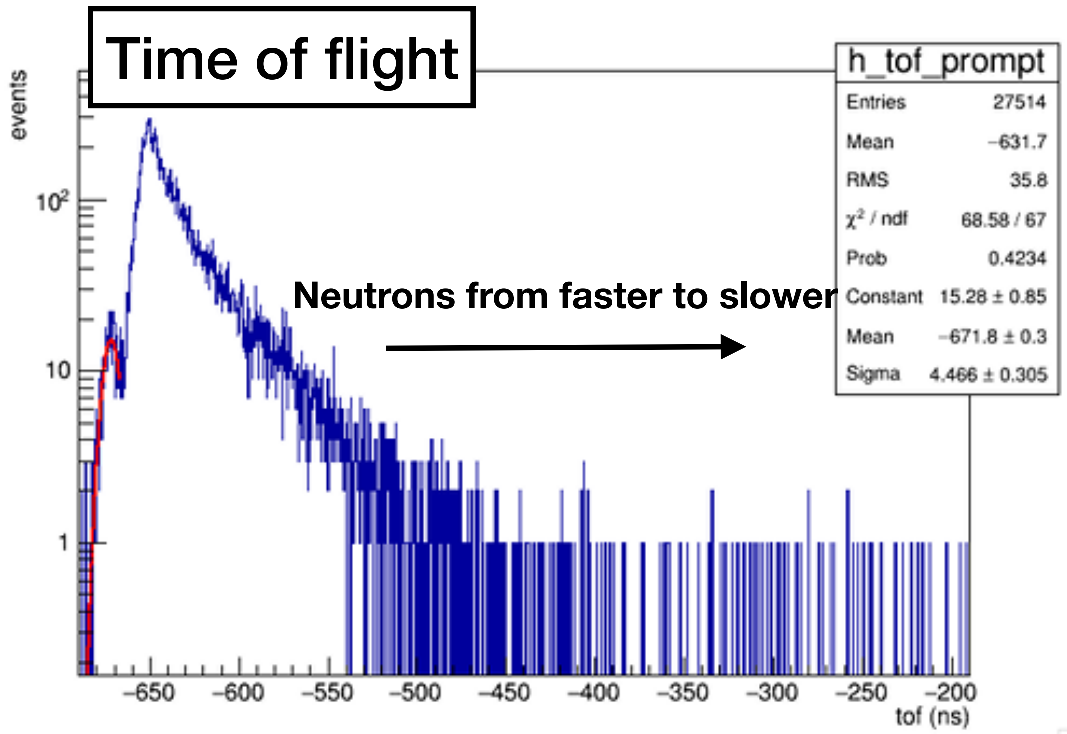
X position [mm]

369-481 MeV

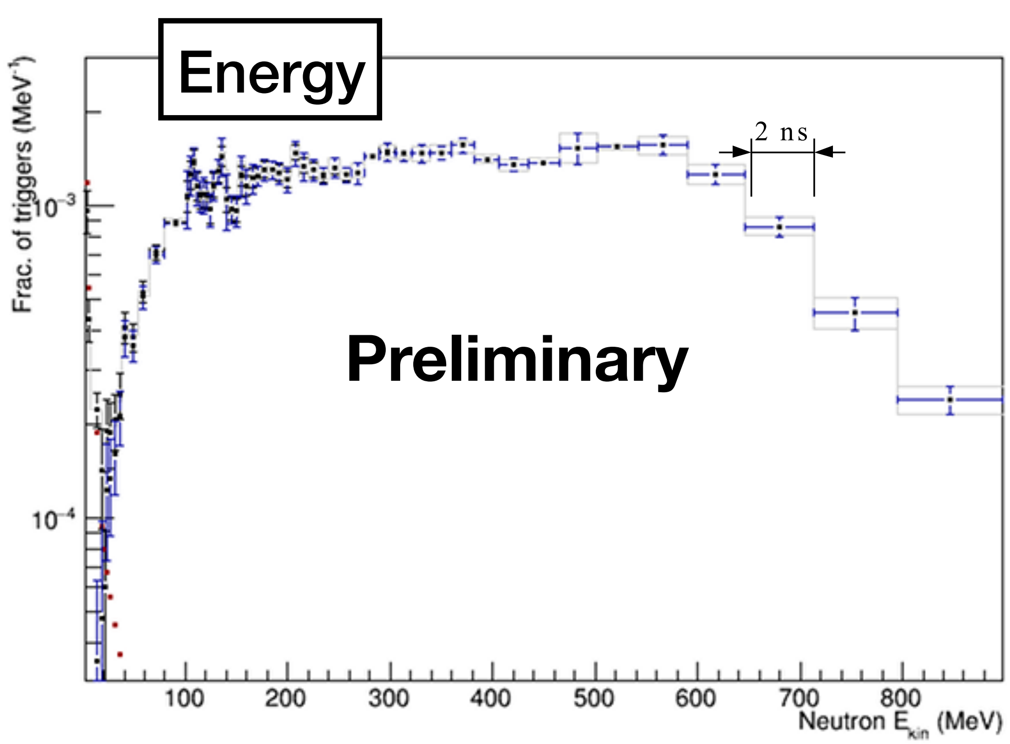


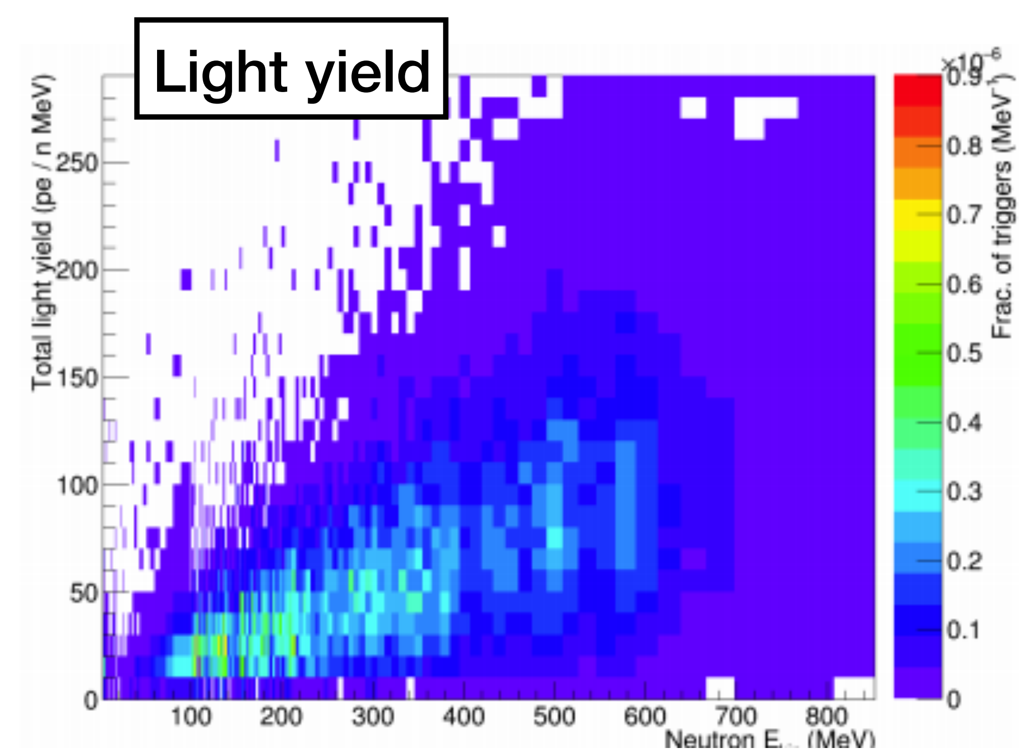
X position [mm]

Results from 2016 Engineering Run



- Neutron time-of-flight (TOF) measured by Argon scintillation in Mini-CAPTAIN using the PDS.
- Neutron energy is determined on each event using the time of flight (Not efficiency corrected; not flux normalized)

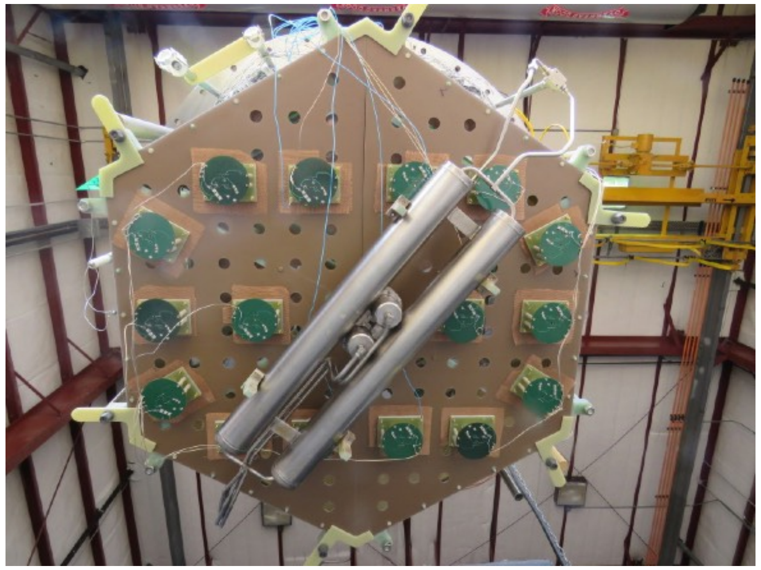


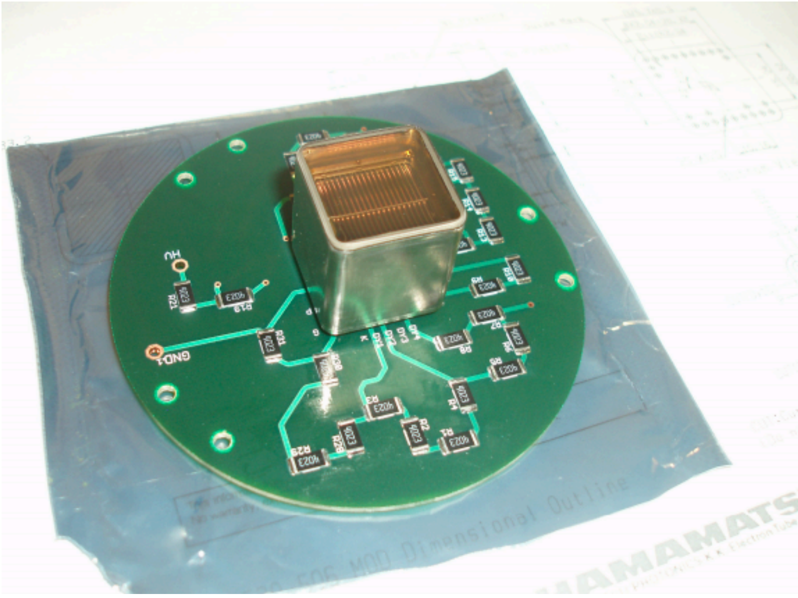


Jorge Chaves

Photon Detection System

- Goals of CAPTAIN PDS:
  - Triggering of non-beam events
  - Evaluation of photon timing from prompt Argon scintillation signal to improve event reconstruction
  - Complement TPC to improve the energy resolution measurements
  - Time of flight for neutron run
- Baseline PDS will provide:
  - 11 pe/MeV in Mini-CAPTAIN
  - 2.2 pe/MeV in CAPTAIN

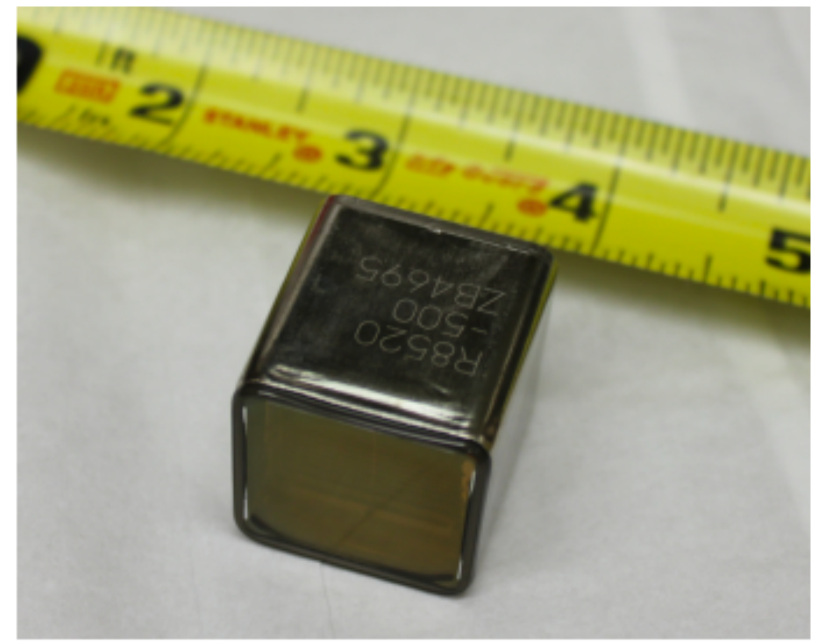


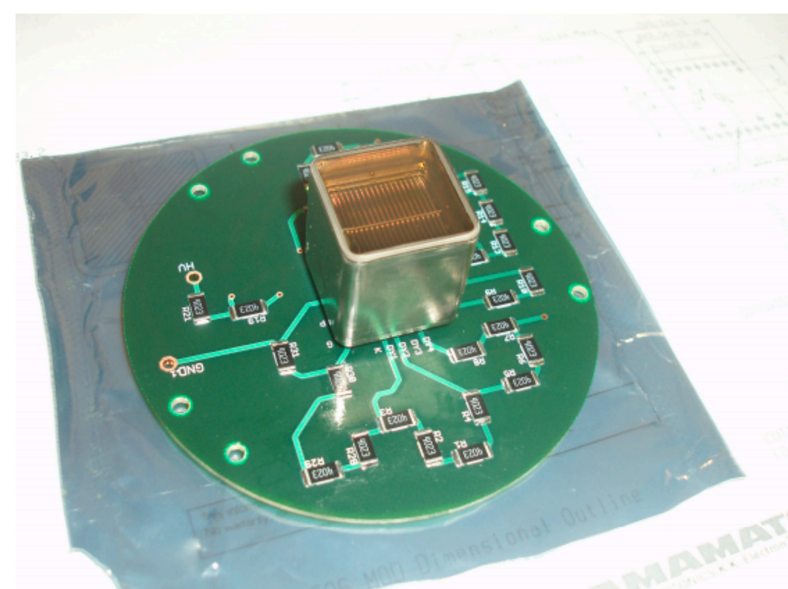


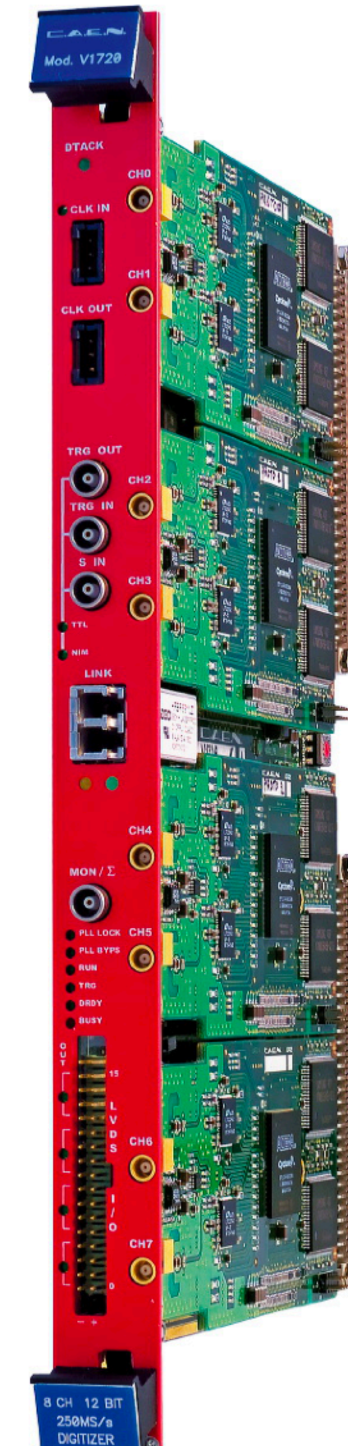
Jorge Chaves

Photon detectors and electronics

- Hamamatsu R8520-506 MOD
  - 1” square
  - 25% QE at LAr temperature, special Bialkali LT
- 24 PMTs installed in Mini-CAPTAIN
- Digitizer:
  - Three CAEN V1720
  - Eight channels each, 250 MSamples
  - 12-bit digitizer across 2 Vpp





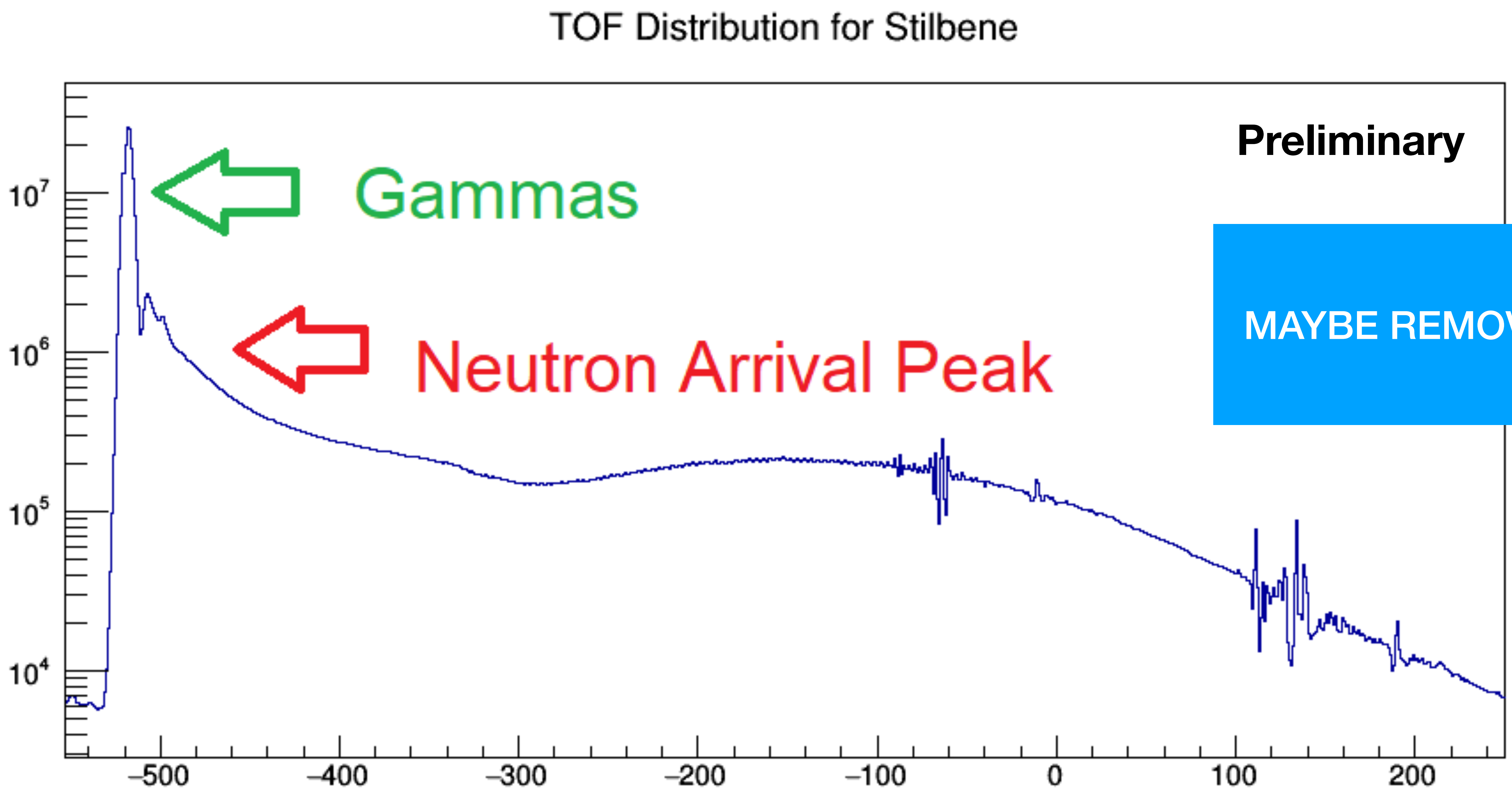


Jorge Chaves

Physics run at WNR

- Significant improvement in LAr purification system before the 2017 Physics Run
- Criotec liquid purification (similar to that used on ARGONTUBE arXiv:1304.6961)
- Recirculation system designed by UCLA, LANL and Penn.
- Thin Stilbene scintillator implemented as a neutron flux monitor (cross-calibrated with the fission chamber)

Photon counts from stilbene



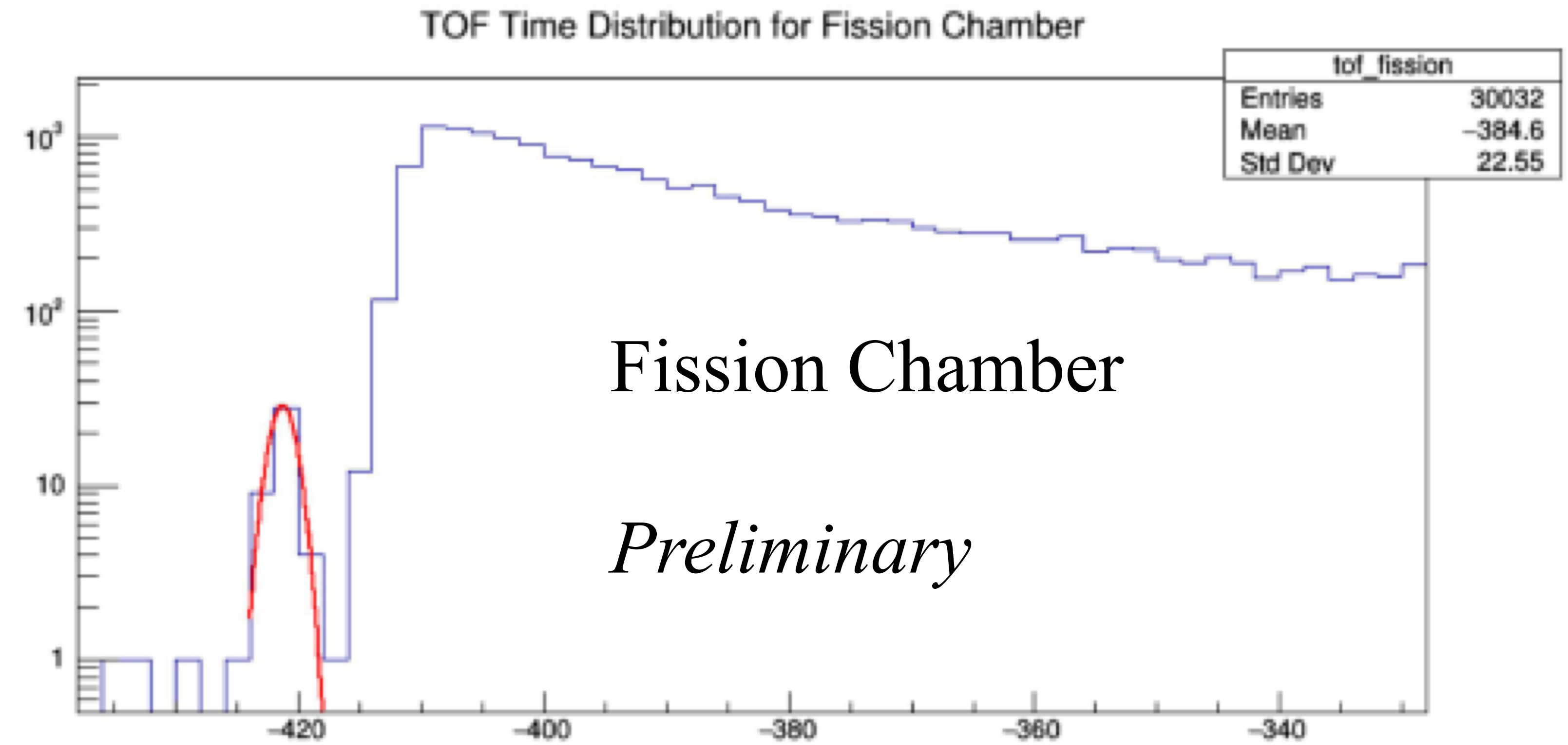
MAYBE REMOVE

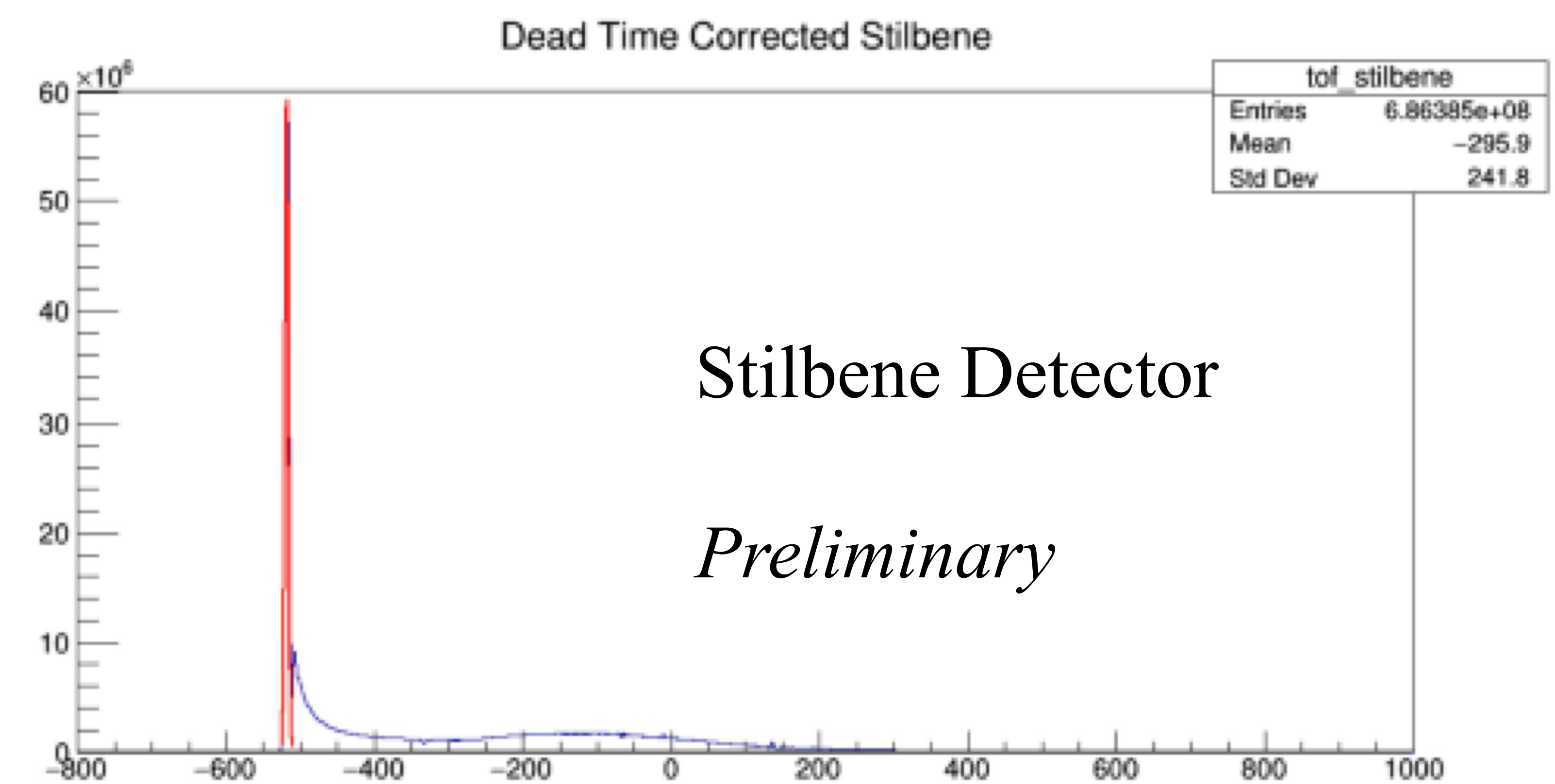
- Photons seen by stilbene detector
- Clear gamma and neutron peaks

Jorge Chaves

Flux detector data

Very preliminary results integrated over low and high intensity running



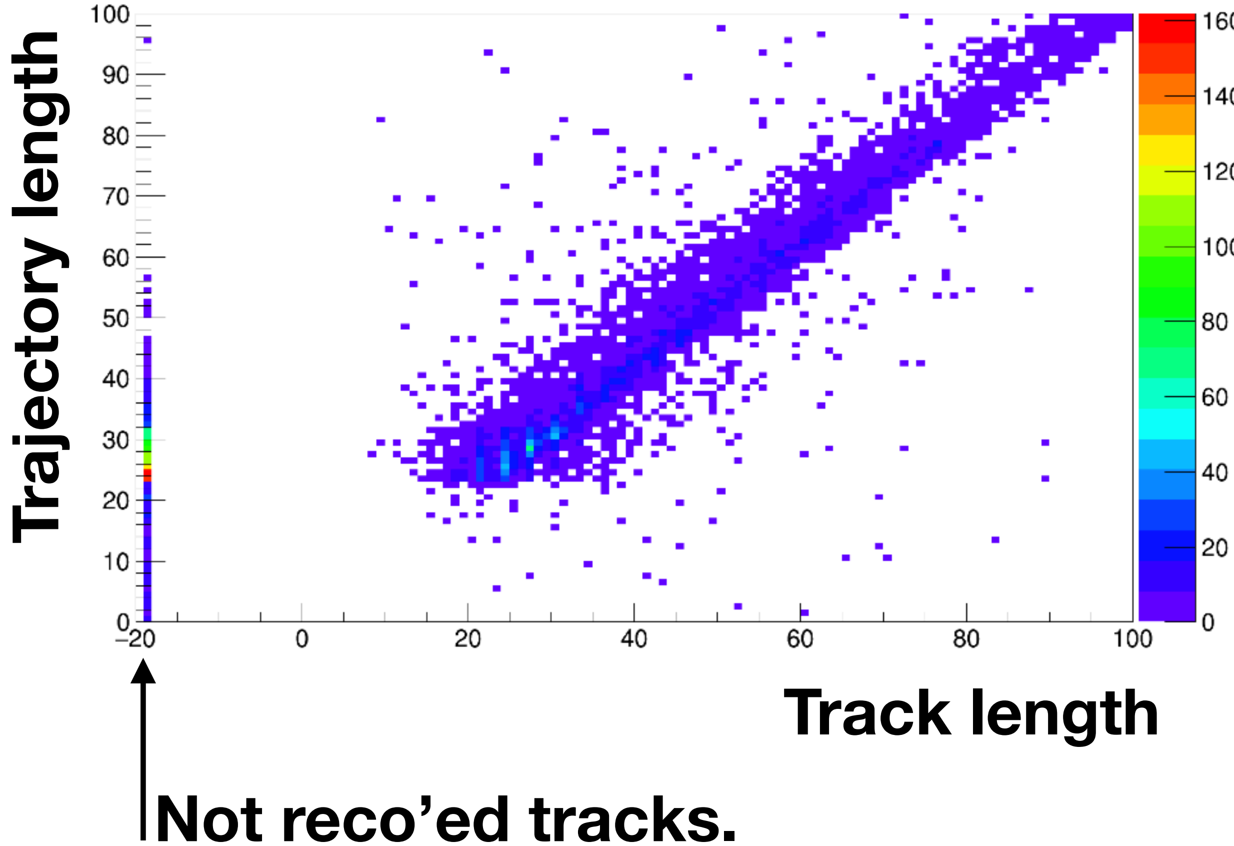


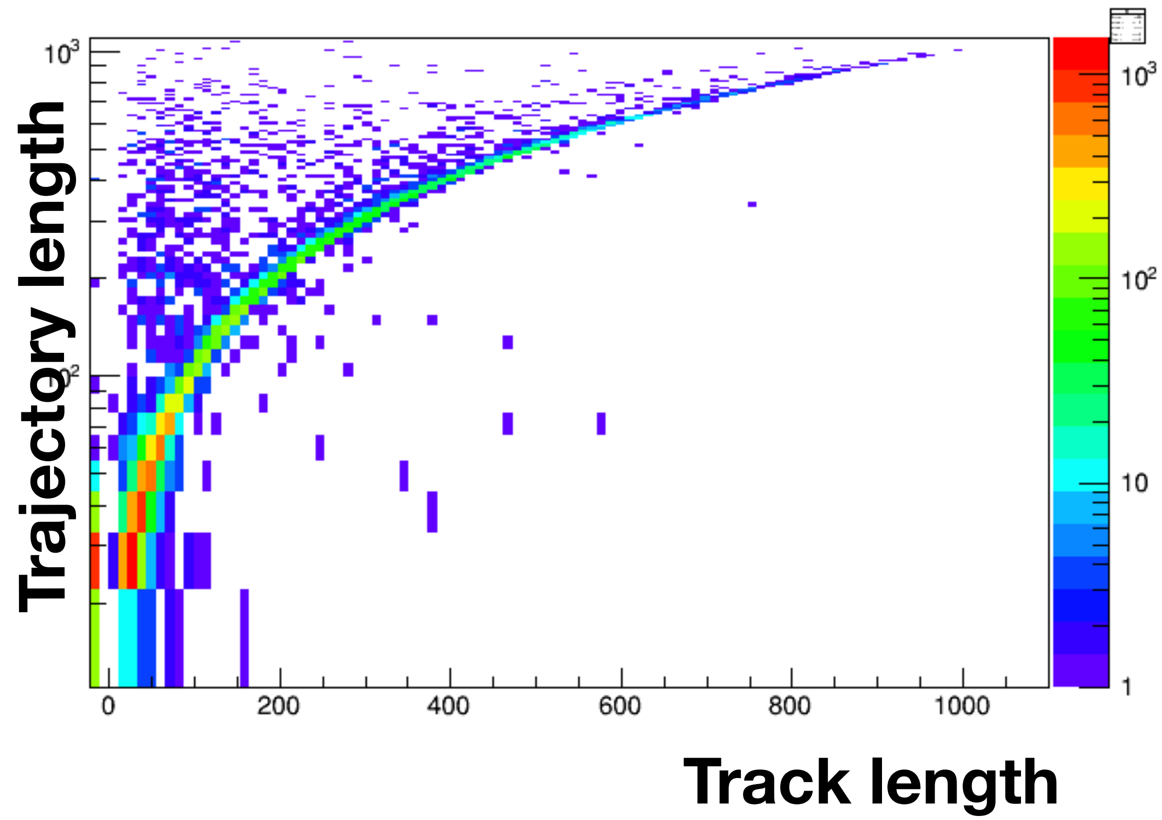
Jorge Chaves

Hamamatsu R8520-506 MOD

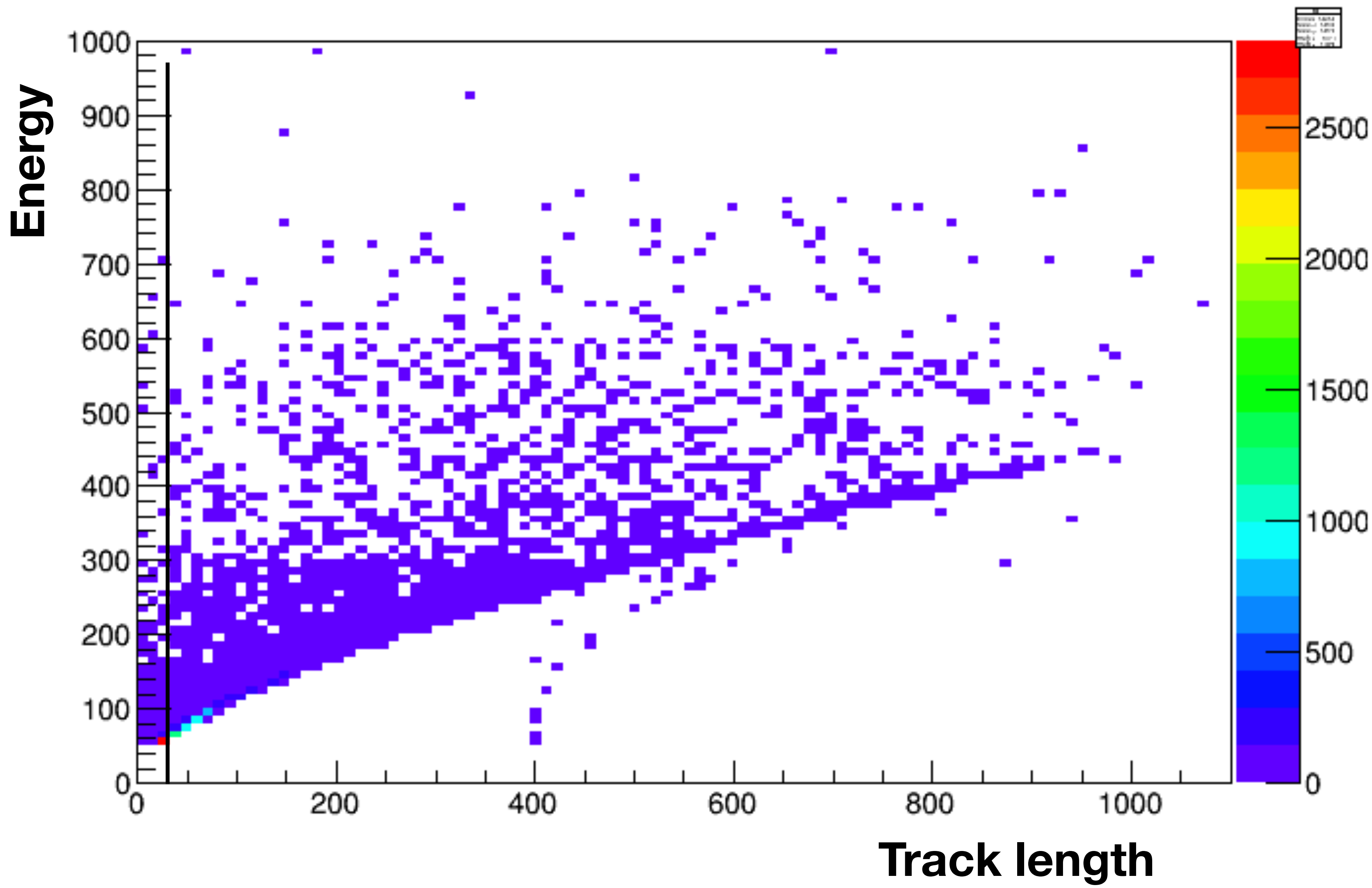
- 26 mm (1 in) square, 10 stages
- operation from -186º to +50º C
- max pressure 5 atm • spectral response: 300-650 nm
- QE at 340 nm*: 25%
- borosilicate glass window
- effective photocathode area 22 mm x 22 mm
- operating voltage +800 V (max +900 V)
- max anode current 0.1 mA
- typical gain* 106
- dark current* typically 2 nA (max 20 nA)
- rise time* 1.8 ns

Track lengths

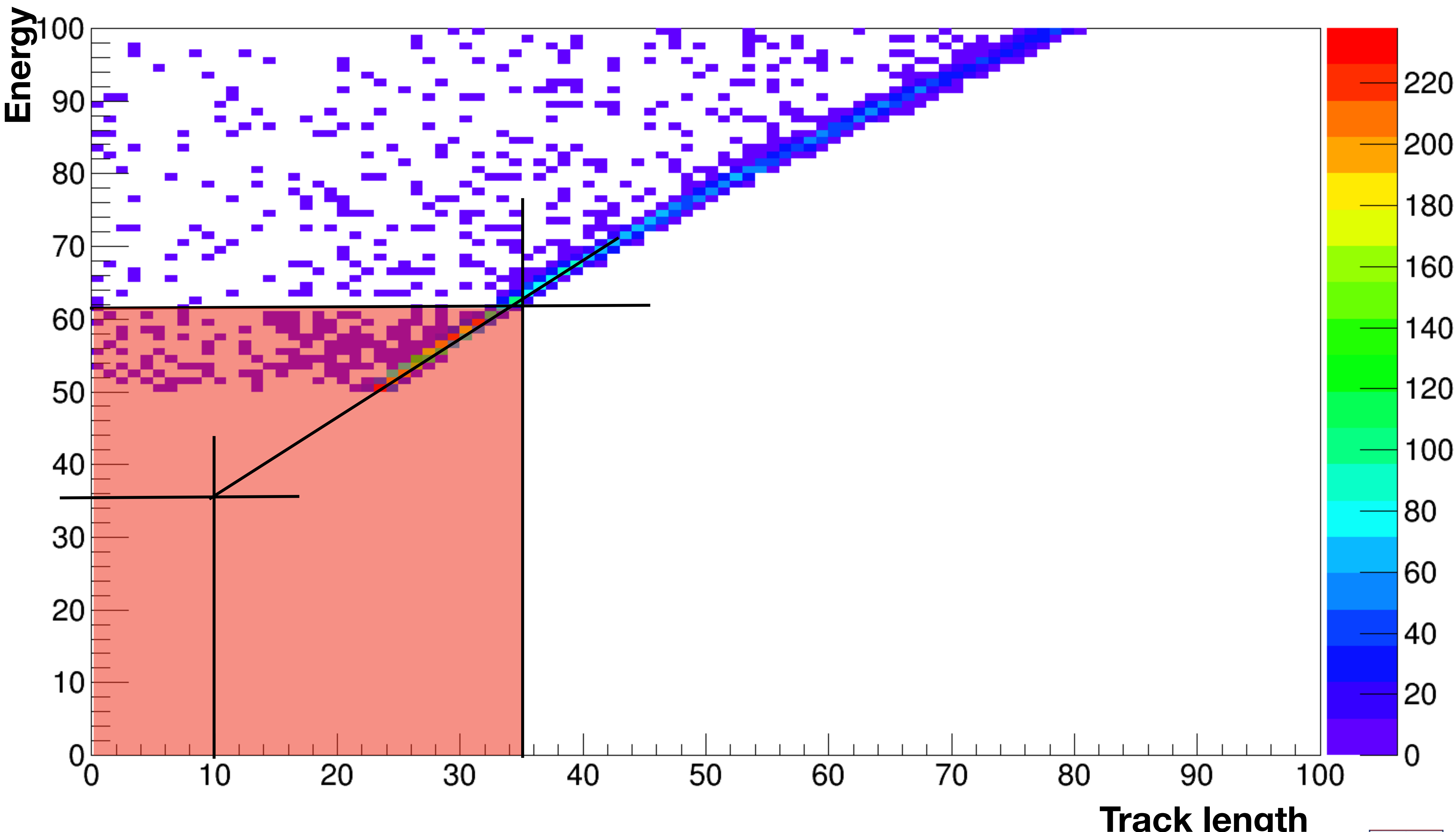




Energy threshold



Energy threshold



Jorge Chaves

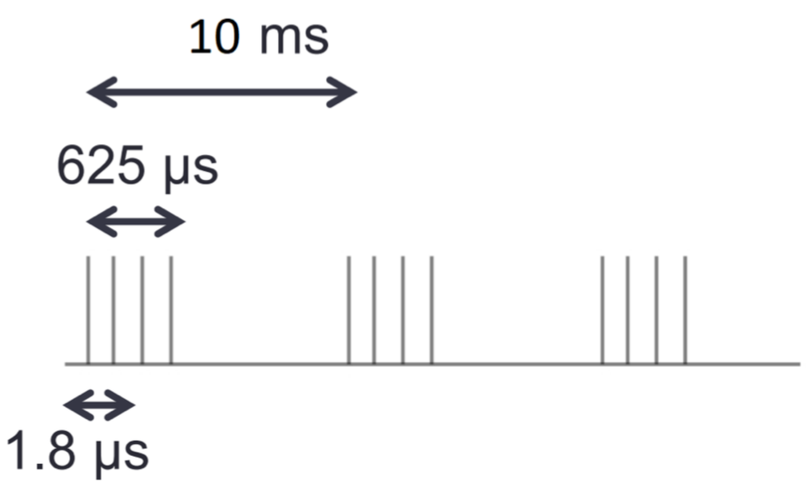
	All tracks single run	2826
1	-300 < Z position < 0	748
2	-200 < Y position < 0	1186
3	-400 < X position < 400	2185
4	-400 < X position < 0	928
5	Track length > 35 mm	2625
6	Neutron energy > 0 MeV	680
	1+2+3	392
	1+2+4	137
	1+2+3+5	351
	1+2+4+5	124
	1+2+3+5+6	321
	1+2+4+5+6	117

Geometric cuts

Quality cuts

Stilbene Setup: The Beam

- The beam creates a trigger by interacting with a coil to create the RF pulse
- The RF pulse is composed of large macropulses that are 625 us in width, with a 10 ms delay between macropulses
- The macropulses are composed of micropulses that are 1.8 us in width



4